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THE ROYAL AERONAUTICAL SOCIETY

JULY 1960

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THE ROYAL AERONAUTICAL SOCIETY

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None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTE: Under the revised By-Laws, allowed on 11th January 1960, the President of each Division and the Chairman of each Section of the Society is a Member of Council by reason of his office.

NOTICES

Astronautics and Guided Flight Section
Lecture 8th July

The U.S. Space and Astronautics Programme

Captain R. F. Freitag, U.S.N., is to address the Astronautics and Guided Flight Section of the Society on "The U.S. Space and Astronautics Programme" *on 8th July* 1960 *at* 6.30 *p.m. at the Institution of Mechanical Engineers, 1 Birdcage Walk, London S.W.*1.

The Annual General Meeting of the Section will be held *before* the Lecture at 4 Hamilton Place, W.1 at 5.30 p.m.

Captain Freitag, an Associate Fellow of the Society, has served continuously in the guided missile and rocket field since 1945 and has recently been appointed Astronautics Officer, Bureau of Naval Weapons, Navy Department, Washington.

August Bank Holiday

The Offices of the Society will be closed from Friday afternoon, 29th July until 9 a.m. on Tuesday 2nd August.

Associate Fellowship Examinations, December 1960

The closing date for Candidates in the United Kingdom for the December 1960 Examinations is 31st August. Entry forms may be obtained from the Secretary. The closing date for entries outside the United Kingdom was 30th June.

Alan Marsh Award and Medal

The Alan Marsh Medal, " awarded to a British Pilot in recognition of outstanding helicopter pilotage achievement," has been awarded to Flight Sgt. B. Breach of No. 228 Squadron R.A.F. In December, 1959 Flight Sgt. Breach displayed exemplary courage, resolution and pilotage skill in rescuing all five crew members of the North Carr Lightship, which in severe gale conditions was dragging its moorings and in imminent danger of foundering.

Mr. A. C. Jolly of the College of Aeronautics, Cranfield has won the Alan Marsh Award, which is awarded to a British Student who has shown exceptional ability in technical study in the rotary wing field. The award consists of five hours flying training on helicopters.

The medal and award of the former Helicopter Association of Great Britain, now the Rotorcraft Section of the Society, will be presented at the Section's Annual Dinner in September, 1960. In future they will be presented, with the Society's other awards, at the Wilbur Wright Memorial Lecture.

One-Year Course in Space Technology

A one-year Post-Graduate Course in Space Technology, beginning 10th October 1960 is offered by the College of Aeronautics. Students who successfully complete the course will be awarded the Diploma of Advanced Engineering.

Applicants should generally be graduates in a branch of science or engineering or have equivalent qualifications. Further information and forms of application may be obtained from The Warden, The College of Aeronautics, Cranfield, Bletchley, Bucks.

Joint Summer Meeting on Non-Destructive Testing

A Conference on the Theory and Practice of Ultrasonic Inspection is to be held at the Queens Hotel, Cheltenham, from 22nd-24th September 1960. The arrangements are being made jointly by the Institute of Physics' Non-Destructive Testing Group, The Society of Non-Destructive Examination and the Non-Destructive Testing Society of Great Britain. Further details may be obtained from the Conference Secretary, Mr. I. M. Barnes, Materials Laboratory, de Havilland Propellers Ltd., Hatfield, Herts.

The Lecture Theatre

The inauguration of the Lecture Theatre will be on Friday, 28th October 1960. Further particulars will be announced later.

Birthday Honours List, June 1960

The President and Council congratulate the following members who were included in the Birthday Honours List:—

G.C.B.	Admiral Sir Caspar John (*Companion*).
K.B.E.	Dr. R. Cockburn (*Associate Fellow*).
K.B.	P. Ll. Hunting (*Companion*).
C.B.	Air Vice-Marshal R. A. Ramsay Rae (*Associate Fellow*).
O.B.E.	R. J. Clayton (*Associate* Fellow).
M.B.E.	D. Cemm (*Associate Fellow*).

Honours Awarded to Members

Sir Frederick Handley Page (*Honorary Fellow*) has been awarded the gold Albert Medal of the Royal Society of Arts for 1960, " for leadership in the design and manufacture of aircraft."

Squadron Leader W. R. Gellatly (*Associate Fellow*) has been awarded the Derry and Richards Medal by the Guild of Air Pilots and Air Navigators.

Agricultural Aviation Group

The Group Committee for 1960-61 is as follows:—

Mr. S. W. G. Foster (*Chairman*)	Mr. C. J. Fooks
	Mr. E. D. King
Mr. R. C. Amsden	Mr. C. H. Latimer-Needham
Dr. R. D. Blackett	Mr. E. H. Smith
Mr. F. C. Clay	Mr. H. G. Winton

Acknowledgment

The Council wish to thank Swiss Air Transport Co. Ltd. for presenting to the Society's Air Mail Collection first flight covers flown on Swissair's first direct service Zurich-Warsaw and on their first DC-8 jet service Zurich-Geneva-New York.

Second International Congress of the Aeronautical Sciences, September 1960

The Second International Congress of the Aeronautical Sciences will be held in Zurich, Switzerland from 12th-16th September 1960.

The technical sessions will be held in the Grosser Horsaal fur Experimentalphysik of the Eidgenossische Technische Hochschule, Gloriastrasse 35, Zurich 6. Dr. Theodore von Kármán, President of the I.C.A.S., will preside. Papers will be presented in English, French and German and interpreting equipment will be provided.

A special Ladies Programme will be arranged. A Reception will be held on Monday evening, 12th September to which all delegates will receive invitations and a banquet will be held on Friday evening, 16th September in the Convention Hall. Tickets for the banquet, approximately 16 Swiss francs, will be sold at the Congress.

Hotel arrangements are being handled by Kuoni's Tourist Office Limited, Bahnhofstrasse 60, Zurich and reservations should be made quickly as accommodation in Zurich is difficult to obtain.

Members of the Society wishing to attend the Congress should apply immediately to the Secretary, 4 Hamilton Place, for application forms.

The lecture programme is given overleaf.

MONDAY, 12th SEPTEMBER

10 a.m. New Physics Hall

Opening Session

Daniel and Florence Guggenheim Memorial Lecture

The Role of Entropy in the Aerospace Sciences—Jakob Ackeret, Prof., Institut für Aerodynamik, Eidgenössische Technische Hochschule, Switzerland.

2 p.m. New Physics Hall

Hypersonic Flow

Possibilités et Limites Actuelles de la Théorie des Ecoulements Hypersoniques—Jean Pierre Guiraud, Ingénieur de Recherches, ONERA, France.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

The Uses of Shock Tubes for Research on Hypersonic Flow—D. W. Holder, Dep. Ch. Scien. Officer, and D. L. Schultz, Prin. Scien. Officer, National Physical Laboratory, U.K.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

2 p.m. Small Physics Hall

Boundary Layer Flow

Beiträge zur Theorie der dreidimensionalen Grenzschichten —J.A. Zaat, Nationaal Luchtvaartlaboratorium, Holland.

Instability of Laminar Boundary Layers—J. T. Stuart, Prin. Scien. Officer, Aero. Div., Natl. Physical Lab., U.K.

Some Aspects of Boundary Layer Transition at Subsonic Speeds Itiro Tani, Prof., Aeronautical Res. Inst., Univ. of Tokyo, Japan.

Boundary Layer Transition at the Leading Edge of Thin Wings and its Effect on General Nose Separation—R. A. Wallis, Sr. Scien. Officer, Australian Def. Scien. Svce, Aeronautical Res. Labs., Dept. of Supply, Australia.

Boundary Layer Separation at High Speeds—A. Naumann, Prof., Deutsche Versuchsanstalt für Luftfahrt, Germany.

TUESDAY, 13th SEPTEMBER

8.30 a.m. New Physics Hall

Boundary Layer, Transonic and Supersonic Flow

Aircraft Shapes and Their Aerodynamics for Flight at Supersonic Speeds—Dietrich Küchemann, Head, Supersonics Div., Royal Aircraft Estab., U.K.

Aerodynamic Design of Swept Wings and Bodies for Transonic Speeds—R. C. Lock and E. W. E. Rogers, Prin. Scien. Officers, Aero. Div. Natl. Physical Lab., U.K.

The Design of Wing Sections for Swept Wings at Transonic and Supersonic Speeds—H. H. Pearcey, Sr. Prin. Scien. Officer, Aerodyn. Div., Natl. Physical Lab., U.K.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

8.30 a.m. Small Physics Hall

Fatigue of Materials

Stress Corrosion Cracking of High Strength Steel—or Hydrogen Embrittlement—Ivar Weibull, Head of Materials Lab., Saab Aircraft Co., Sweden.

Etude Microscopique de la Fissuration par Fatigue à Haute Fréquence—François Girard, Ingénieur de Recherches, ONERA, France.

The Notched Fatigue Properties of High Tensile Steels—W. A. Morgan, Hd., and R. K. Buhr, Sr. Scien. Officer, Ferrous Metals Sect., Phys. Metallurgy Div., Dept. of Mines and Tech. Surveys, Canada.

Some Aspects of Fatigue in Aircraft Structures—J. Schijve, Structs. and Mtls. Dept., Natl. Aeronautical Res. Inst., Holland.

2 p.m. New Physics Hall

Supersonic Flow

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

Theoretical and Experimental Studies of Cambered and Twisted Wings Optimized for Flight at Supersonic Speeds—C. E. Brown, Ch., Theoretical Mech. Div., E. B. Klunker, and F. E. McLean, Aeronautical Res. Engrs., Langley Res. Center, NASA, U.S.A.

Some Experimental Results of Generating High Frequency Oscillating Shock-Waves and Oscillating Shock-Wave Boundary Layer Interaction at Supersonic Speeds—Wladyslaw Fiszdon, Prof. of Aeronautics, Tech. Univ. Warsaw, Poland.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

2 p.m. Small Physics Hall

Aerothermochemistry

Some Contributions to Laminar Flame Theory—Gregorio Millan, Adviser, and Ignacio da Riva, Aeronautical Engr., Instituto Nacional de Técnica Aeronautica (INTA) Spain.

Etude de la Combustion dans les Fusées à Lithergol—André Moutet, Chef de Groupe, and Marcel Barrere, Chef de Division, ONERA, France.

Effect of a Shock-Wave in a Burning Solid Propellant—Ellis M. Landsbaum, Res. Group Supvsr., Solid Propellant Rockets Sect., Jet Prop. Lab., CIT, U.S.A.

Elucidations of Combustion Instability in Solid Propellant Rockets—Seiichiro Kumagai, Prof., Dept. of Aeronautics, Faculty of Engrg., Univ. of Tokyo, Japan.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

WEDNESDAY, 14th SEPTEMBER

8.30 a.m. New Physics Hall

Non-Stationary Transonic Flow

Non-Stationary Transonic Flow Past Aerofoil and Revolution Bodies at a Zero Angle of Attack—Carlo Ferrari, Prof., Politecnico, Centro Dinamica dei Fluidi, Italy.

A Paper to be Presented by the Academy of Sciences, U.S.S.R.

8.30 a.m. Small Physics Hall

Air Transport

Operations Research in the Basic Design of YS-11 Transport Airplane—Hidemasa Kimura, Prof. of Aeronautical Engrg., Faculty of Engrg., Nihon Univ.; Jiro Kondo, Prof., Tokyo Univ.; and Shizuo Kikuhara, Tech. Adviser, Shin-Meiwa Indus. Co., Ltd., Japan.

Airline Economy in the Turbine Era—Franklin W. Kolk, Dir. of Engrg. R. & D., American Airlines, Inc., U.S.A.

10.15 a.m. New Physics Hall

General Lectures

Physik des Jet-Stream—Walter Georgii, Dir., Deutsche Forschungsanstalt für Segelflug, Institut für Flugforschung, Germany.

The Aerodynamics of Jet Flaps—John Williams, Supt., Low-Speed Tunnels Div., Aero. Dept., Royal Aircraft Establ., U.K.

THURSDAY, 15th SEPTEMBER

8.30 a.m. New Physics Hall

Magneto Fluid Dynamics

Sub- and Super-Alfvénic Flows Past Bodies—W. R. Sears, Dir., and E. L. Resler, Jr., Prof., Grad. School of Aeronautical Engrg., Cornell Univ., U.S.A.

Aerophysical Studies at Hypersonic Velocities in Free Flight Ranges—C. J. Maiden, Hypersonic Physics Group, Canadian Armament Res. and Dev. Establ., Canada.

Magneto-Fluid-Dynamic Shear Turbulence—Luigi G. Napolitano, Assoc. Prof. of Aerodyn., Univ. of Naples, Italy.

Magnetoaerodynamics in Japan—Isao Imai, Prof., Dept. of Physics, Faculty of Science, Univ. of Tokyo, Japan.

8.30 a.m. Small Physics Hall

Structures and Fatigue

Statistical Methods for Fail-Safe Design with Respect to Fatigue of Aircraft Structures—Bo K. O. Lundberg, Dir., The Aeronautical Res. Inst. of Sweden.

A Method of Selfinduced Alternating Loads Alleviation of Airframes—F. Misztal, Prof., Politechnical Univ., Poland.

Einfluss des Start-Landelastwechsels auf die Lebensdauer von böenbeanspruchten Flugzeugflügeln—Ernst Gassner, Laboratorium für Betriebsfestigkeit, and Karl F. Horstmann, Maschinenfabrik Carl Schenk, G.m.b.H., Germany.

Protection of Aircraft Structures Against High Temperatures—Wilfred M. Dukes, Ch. of Struc., Aero-Space Dept., Niagara Frontier Div., Bell Aircraft Corp., U.S.A.

2 p.m. New Physics Hall

Flows with Chemical Reactions

Limites en Vitesse et Altitude des Propulseurs Utilisant l'Air Atmospherique—Albert Gozlan, Chef de Department (Propulsion), Nord-Aviation, France.

Hypersonic Ram-jets—Donald L. Mordell, Dean, Faculty of Engrg., and J. W. Swithenbank, Assoc. Prof. of Mech. Engrg., McGill Univ., Canada.

Research Problems on Recombination and Condensation in Nozzles—Walter T. Olson, Ch. Propulsion Chem. Div., Lewis Res. Center, NASA, U.S.A.

Schliereninterferenzaufnahmen von Kopfwellen und Grenzschichten dissoziierter Gase—Herbert Oertel, Physiker, Deutsch-Französisches Forschungsinstitut Saint-Louis, France.

2 p.m. **Aeroelasticity** Small Physics Hall

Predictions of Lifting Surface Flutter at Supersonic Speeds—Holt Ashley, Assoc. Prof. of Aeronautics and Astronautics, MIT; Walter Mykytow, Asst. Ch., Dynamics Br., Aircraft Lab., Wright Air Dev. Div., U.S.A.F.; and John Martuccelli, Res. Engr., Aeroelastic and Struc. Res. Lab., MIT, U.S.A.

Elastic Stability and Vibration of Slender Body in Supersonic Flow—Sylwester Kaliski, Prof., and Jerzy Kacprzynski, Master Engr., Dept. of Vibrations, Polish Academy of Sciences, Poland.

Determination des Vitesses Critiques Transitoires d'un Engin Supersonique en Vol Accéléré—Robert Mazet, Prof., Dir. Scientifique, and Eugene Bonneau, Chef de Groupe de Recherches, ONERA, France.

Vibrations of Viscoelastic Plates and Shells due to Rapid Heating—Witold Nowacki, Prof., Polish Academy of Sciences, Poland.

FRIDAY, 16th SEPTEMBER

8.30 a.m. **Entry from Space** New Physics Hall

Manned Re-Entry at Super-Satellite Speeds—Robert B. Hildebrand, Ch., Advanced Syst. Res., Aero-Space Div., Boeing Airplane Co., U.S.A.

Effects of Non-Equilibrium Flows on Aerodynamic Heating During Entry into the Earth's Atmosphere from Supercircular Orbits—Glen Goodwin, Ch., and Paul Chung, Res. Scien., Heat Transfer Br., Ames Res. Center, NASA, U.S.A.

Radiative and Ablation Cooling for Manned Re-Entry Vehicles—Leonard Roberts, Aeronautical Res. Engr., Langley Res. Center, NASA, U.S.A.

Sur l'Aérothermodynamique des Parois Fongibles—Th. Moulin and J. J. Bernard, ONERA, France.

8.30 a.m. Small Physics Hall

Aerospace Medicine

Zur Frage der Auswahlmethoden für Besatzungen unkonventioneller Flugkörper—Siegfried Ruff, Prof., Institut für Flugmedizin, Deutsche Versuchsanstalt für Luftfahrt e. V., Germany.

Body Susceptibility to High Accelerations and to Zero Gravity Condition—Rodolfo Margaria, Prof. of Physiology, Institute of Human Physiology, Medical School, Univ. of Milan; and T. Gualtierotti, Institute of Human Physiology, Univ. of Sassari, Italy.

A Review of Biologic Exposures to Space Environments—Brig. Gen. Don Flickinger, Asst. to Commander for Bioastronautics, U.S.A.F. (M.C.), U.S.A.

Comportement de Quelques Fonctions Perceptives et Motrices Pendant le Passage de Deaux a Zéro G, Obtenu au Moyen de la Tour de Subgravité. Influence de l'Entrainement—Tomaso Lomanaco, Dir. des Services de Santé de l'Aviation Militaire, Corps de Santé, Aviation Militaire Italienne, Aristide Scano, IAF (MC), and Franco Rossanigo, IAF (MC), Centre d'Etudes et de Recherches de Médécine Aéronautique, Italy.

2 p.m. New Physics Hall

Space Flight

Power Generation Systems for Use in Space—Henry O. Slone and Seymour Lieblein, Aeronautical Res. Engrs., Nuclear Reactor Div., Lewis Res. Center, NASA, U.S.A.

Guidance of Space Vehicles by Radio Measurements and Command—A. R. M. Noton, Group Supervisor, Jet Propulsion Lab., CIT, U.S.A.

Discoveries from Satellite Orbits—D. G. King-Hele, Prin. Scien. Officer, Royal Aircraft Establ., U.K.

It is hoped that pre-prints of all the papers will be on sale at the Congress at a nominal fee. Publication of the papers and Discussions is planned later in the form of Proceedings.

School of Welding Technology Courses

The following courses will be held by the School of Welding Technology during September and October 1960: —Welded Pressure Vessels, 26th-30th September; Residual Stresses and Stress Relief, 10th-11th October; Practical Control of Distortion, 12th-14th October; Metal Spraying, 24th-27th October.

Full details may be obtained from the Institute of Welding, 54 Princes Gate, Exhibition Road, London S.W.7.

News of Members

Wing Cdr. R. P. Beamont (*Associate*), has been appointed a Special Director, English Electric Aviation Ltd.

L. H. Bedford (*Fellow*) has been appointed Director of Engineering, Guided Weapons Division, English Electric Aviation Ltd.

E. L. Beverley (*Associate*) formerly Commercial Manager, English Electric Guided Weapons Division, is now Sales Manager (Guided Weapons), British Aircraft Corporation.

P. Blandford (*Associate Fellow*) formerly General Service Manager at Vickers-Armstrongs (Aircraft) Ltd., is now on the management staff of Ferodo Ltd., Derbyshire.

Sqn. Ldr. C. E. F. Brown (*Associate Fellow*) formerly No. 8 Joint Staff T.11, Australia, has been posted to the Air Ministry for Staff Duties in the Directorate of Weapons Engineering.

S. R. Brown (*Associate Fellow*) formerly Assistant Civil Air Attaché (Telecommunications), British Embassy, Washington, is now Senior Signals Officer, Ministry of Aviation.

Flt. Lt. S. L. Bugg (*Associate Fellow*) formerly a lecturer at the R.A.F. Technical College, Henlow, is now at the Air Ministry D.D.I. (Tech.).

Viscount Caldecote (*Associate Fellow*) has been appointed Managing Director and Chief Executive Guided Weapons Division, English Electric Aviation Ltd., and Executive Director, Guided Weapons, British Aircraft Corporation.

Flt. Lt. G. M. G. Cooper (*Graduate*) formerly at the Flying Training School, Ternhill, has been posted to Central Servicing Development Unit, Dereham.

D. C. Crowther (*Associate Fellow*) formerly Research and Development Engineer, Rolls-Royce Ltd., Barnoldswick Division, has moved to Derby as Organisation and Methods Engineer.

D. M. Devenish (*Graduate*) formerly a Lecturer at the College of Aeronautical and Automobile Engineering, Chelsea, is now in the Aerodynamics Department, Bristol Aircraft Ltd.

Kenneth Dewar (*Associate*), formerly with Saunders-Roe Ltd., is now Publicity Officer and Exhibition Liaison Officer, Hawker Siddeley (Hamble) Ltd., Southampton.

A. L. R. Dzininski (*Graduate*) formerly an Engineer with de Havilland Propellers Ltd., London Office, is now a Mechanical Engineer in the Uranium Magnox Project Office, Atomic Power Division, English Electric Co. Ltd., Whetstone.

Sir George R. Edwards (*Honorary Fellow*) has been appointed Executive Director, Aircraft, British Aircraft Corporation.

Sqn. Ldr. G. B. Foort (*Associate*) has been appointed Senior Technical Officer, R.A.F. Acklington.

Captain R. F. Freitag (*Associate Fellow*) formerly Planning Officer, Headquarters Pacific Missile Range, California, is now Astronautics Officer, Bureau of Naval Weapons, Navy Department, Washington.

G. F. Gilmore (*Associate Fellow*) formerly Lecturer in Mechanical Engineering, Hendon Technical College, is now Head of the Department of Engineering and Building, Stafford College of Further Education.

W. G. Haggitt (*Associate*) formerly Works Manager, Charles Hill and Co. Ltd., Birmingham, is now a Production Engineer, Joseph Fray Ltd., Birmingham.

T. L. Hall (*Associate Fellow*) formerly a Technical Officer, Hunting-Clan Air Transport at London Airport, is now a Technical Sales Engineer, Civil Aircraft Development Group, Vickers-Armstrongs (Aircraft) Ltd., Weybridge.

Wing Cdr. R. E. W. Harland (*Associate Fellow*) formerly British Joint Services Mission, U.S.A., has been posted to R.A.F. Station, Swanton Morley, Dereham.

N. H. Hooke (*Associate*) formerly a Senior Designer, Bristol Siddeley Engines Ltd., Coventry, is now a Senior Designer, Rolls-Royce Ltd., Derby.

L. R. I'ANSON (*Associate Fellow*) formerly a Senior Designer, English Electric Aviation Co., Warton, is now a Senior Engineer (Thermodynamics), Canadair Ltd.

L. W. LARKE (*Associate Fellow*) is now at the Royal Aircraft Establishment, Farnborough.

I. R. LIDDELL (*Companion*) formerly Passenger Relations Superintendent, British European Airways, is now Assistant Passenger Services Manager.

E. C. S. LITTLE (*Companion*) formerly at Oxford University, is now working for the United Nations, International Atomic Energy Agency as an adviser to the Burmese Government.

JOHN G. MARSHALL (*Associate Fellow*) formerly on the Engineering Staff, Georgia Division, Lockheed Aircraft Corporation, has been transferred to the Lockheed Missiles and Space Division in Sunnyvale as a Senior Design Engineer, Support Systems Department.

Flt. Lt. R. H. MATHEWS (*Associate Fellow*) formerly attached to de Havilland Propellers Ltd., No. 14 Joint Services Trials Unit (Cardington) is now Engineer Officer, No. 111 Squadron, R.A.F. Wattisham.

Wing Cdr. G. E. MCCULLAGH (*Associate Fellow*) formerly with the Ministry of Defence, is now a Senior Technical Officer, R.A.F. North Coates.

M. J. MOTT (*Associate Fellow*) formerly with the Airspeed Division, de Havilland Aircraft Co., Christchurch, is now in charge of the Structural Test House at Hatfield.

Air Vice-Marshal W. A. OPIE (*Fellow*) formerly Principal Director of Aircraft Research and Development, has been appointed Managing Director, Irwin Technical Ltd., London.

L. W. A. OSBORNE (*Associate*) formerly Assistant Chief Inspector, Fairey Aviation Ltd., is now Chief Inspector, Airwork Services Ltd., Bournemouth Airport.

C. B. A. SCHIFF (*Associate*) formerly Deputy Chief Inspector, Organisation and Procedure, Bedek, Government Aircraft Overhaul Base, is now Assistant Quality Control Manager with the Israel Aircraft Industries, Lod Airport.

V. C. VARCOE (*Associate*) has retired from his post as Sales Manager, Aviation Department, Shell-Mex & B.P. Ltd. He has recently been appointed Honorary Clerk to the Guild of Air Pilots and Air Navigators.

J. E. VARGAS (*Associate*) formerly Assistant to the General Manager, Aeronavis De Mexico, S.A., is now Operations Manager at Cia. Mexicana De Aviacion, S.A.

M. A. WALLIS (*Graduate*) formerly Engineer B, Structural Test Department, Avro Aircraft Ltd., Malton, is now a Test Engineer at Canadian Pratt and Whitney Aircraft Co. Ltd., Canada.

Sqn. Ldr. B. N. WILSON (*Associate Fellow*) formerly Station Electrical Officer, R.A.F. Khormaksar, Aden, is now on the Engineering Staff (Eng. 8C) at H.Q. Bomber Command, High Wycombe.

Lieut. Cdr. A. WORMELL (*Graduate*) formerly Air Engineer Officer, R.N.A.S., is now with the Defect Analysis Section, Naval Aircraft Maintenance Development Unit, Lee-on-Solent.

Rotorcraft Section

HELICOPTER VIBRATION

by

DR. J. P. JONES

Given on 10th June 1960. *To be published.*

LECTURE SUMMARY

The lecture is an account of work at Southampton University on problems of helicopter blade vibration.

The phenomenon of "wake" flutter on airscrew and rotor blades is described. It is shown that the damping of flexural vibrations can become very small and that single degree of freedom torsional oscillations are possible. Tests which have been devised to check the validity of the theory are described and the results obtained are compared with those obtained elsewhere. Apparatus designed for the measurement of the flexural damping in hovering of various rotor configurations is described.

The problem of obtaining the stresses in rotor blades in forward flight, and possible methods of determining the blade motion, are discussed. The apparatus to be used for blade stress measurements and flutter experiments in forward flight is described. It is concluded that only large scale model testing will give satisfactory design information.

ELECTIONS

The following is a list of elections and transfers of membership:—

Associate Fellows

Keith Eric Allen (*from Graduate*)
Ronald Ashford (*from Graduate*)
David Earle Bailey
Norman Arthur Barfield (*from Graduate*)
John William Bayley
David Percy Bottrill (*from Graduate*)
Brian Joseph Brinkworth
John Robert Burton (*from Graduate*)
Giovanni P. Casiraghi
Roy Christie
Frederick Richard Davies
Alan Geoffrey Foskett
Henry William Frost
John Richard Herbert
Raymond John Hilborne
Holavanahalli Narayanarao Krishnamurthy
Louis Francois Georges Legrand
Ronald Douglas Milne (*from Graduate*)
Wieslaw Jozef Pulczynski
Parnell
Donald Pierrepont (*from Graduate*)
Alexander Stewart
John Bernard Prothero Thomas (*from Graduate*)
William Joseph Tippett (*from Graduate*)
Arthur Tomlinson (*from Student*)
Donald William Trebley (*from Graduate*)
Edward Burke Wilford

Associates

George Richard Brown
Gordon Rayner Carlton Copeman
John George Blackburne Daniell
Reginald Gilbert Heron
Alan Cornelius Knight
Ronald Harvey Osborn
Sidney Malcolm Partridge
Herbert Royston Quantick
Anthony Scholefield
Christopher David Walker
James Warburton
Kendall Taylor Wardle
Arthur Owen Williams

Graduates

Robert Frank William Anstee (*from Student*)
William Dean Bryce
Terence Coates (*from Student*)
Colin Samuel Flint
Hugh Richard Geoffrey Harrison
Julian Nayar
Patrick Digby Taaffe O'Connor
Brian John Francis O'Riordan (*from Student*)
Jack Beresford Pearson (*from Student*)
Ian Maxwell Scoggins
Roger Westover Selden (*from Student*)
Lionel Henry Townend (*from Student*)
Gyan Singh Uppal

Students

Hotorwoo M. Alexander
John McKenzie Barron
Edward Jack Butler
John Edward Cupis
Rui Do Carmo de Noronha Da Conceicao Espadinha
Brij Nandan Gupta
Anthony Charles Hemuss
Paul John Lawson
Roger Thomas Munt
Raymond Stanley Neve
Terence John Stickings
Brian Sinclair Wolfe

Companions

Jacques Allez
J. G. Iles
Harvey Pierre Jolly
Henry Kremer
Thomas Edward Lucas
John Fleming Purdy (*from Graduate*)
Francesca S. J. Slaughter

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The Forty-Eighth Wilbur Wright Memorial Lecture

Mathematics and Aeronautics

by

M. J. LIGHTHILL, F.R.S.

(Director, Royal Aircraft Establishment)

The 48th Wilbur Wright Memorial Lecture, "Mathematics and Aeronautics" was given by Mr. M. J. Lighthill, F.R.S., before a large and distinguished audience at the Institution of Mechanical Engineers, 1 Birdcage Walk, on 19th May 1960. Dr. E. S. Moult, C.B.E., B.Sc., F.R.Ae.S., M.I.Mech.E., President of the Society, presided.

As has become the custom, before the lecture was delivered the President presented the awards made by the Council for 1960 for outstanding contributions to aeronautics. In the unavoidable absence of the Secretary he was assisted by Miss E. C. Pike, M.A., A.F.R.Ae.S., Secretary of the Medals and Awards Committee and Editor of THE AERONAUTICAL QUARTERLY. The list of the awards presented on this occasion was published in the June 1960 JOURNAL—(p. XXXII).

The President, introducing the lecturer, reminded the audience that the Wilbur Wright Lecture commemorated the first manned, powered controlled flight by Wilbur Wright at Kitty Hawk, North Carolina on 17th December 1903. The first Wilbur Wright Memorial Lecture was held in 1913 and they had been held each year ever since, through two World Wars; in itself a wonderful record. The custom had been, and would continue to be, to have alternately a lecturer from the United Kingdom and a lecturer from the United States; last year the lecture had been by Mr. McCarthy of Chance Vought and next year again it would be by an American.

The Wilbur Wright Lectures had been a most distinguished series by distinguished lecturers, and he was sure that the lecture that night would be in keeping. His pleasant duty was to introduce Professor Lighthill—or as they had to call him *Mr.* Lighthill now that he was Director of the Royal Aircraft Establishment, which was an even greater distinction. Mr. Lighthill was the youngest Director that the R.A.E. had ever had—that alone was a tribute to Mr. Lighthill's ability and his high standing in the profession. Before joining the Royal Aircraft Establishment Mr. Lighthill was Professor of Applied Mathematics at Manchester University, and for a time, after leaving Cambridge, had worked at the National Physical Laboratory where he applied the mathematics of Cambridge to the problems of aerodynamics. His lecture was on "Mathematics and Aeronautics"; he would ask Mr. Lighthill to deliver the 48th Wilbur Wright Memorial Lecture.

1. Introduction

May I begin by saying how honoured I felt when last year I was selected from, as it were, the academic fringe of aeronautics, to give a lecture in the international series sponsored by this illustrious Society in memory of one of the great innovators and creators of the twentieth-century way of life, Wilbur Wright. This will be the 48th Wilbur Wright lecture, but, although all my famous predecessors have spoken on the subject of aeronautics, this will be the first lecture which has explicitly coupled with it mathematics, with the object of evaluating the contributions which mathematics may have made to aeronautics, while not ignoring such feedback as may have occurred during the process.

I will put my cards on the table at once and say that I regard it as appropriate that mathematics should have waited its turn in this way. It is dangerous to over-value the contribution of mathematics to any branch of engineering, and in a lecture seven years ago In New York I sternly warned an audience of mathematicians against this danger. I said then[12]:

Mr. Lighthill delivering his lecture.

"Mathematics is only one of many valuable ways of viewing the fantastic behaviour of things, and it cannot possibly replace the other essential and essentially different ways like physics, biology, statistics, economics, poetry, love and religion." Here less emphasis is necessary. It is obvious in aeronautics what a variety of human skills and disciplines and wisdoms have to be combined to secure success.

Wilbur Wright's greatest contribution, perhaps, was his recognition of this fact. He saw that the problem was more than a scientific and engineering one. Certainly he attached great importance to basic aerodynamic data (for example, his work on the improvement of Lilienthal's lift curves) and to loading and static stability calculations based on them, and to ingenious mechanisms like his famous one for lateral control. For the wisdom of his approach one may quote from his 1899 letter to the Smithsonian Institution[1], where he wrote: "I am an enthusiast, but not a crank in the sense that I have some pet theories as to the proper construction of a flying machine. I wish to avail myself of all that is already known and then if possible add my mite to help on the future worker who will attain final success." A little later he wrote: "what is chiefly needed is skill rather than machinery," and the context makes it clear that by skill he meant experience in the air aimed at developing the right responses in the aviator. This experience the brothers were to accumulate soon afterwards, gliding over the sands at Kitty Hawk and so educating their reflexes to collaborate with their premeditated efforts. At the same time they were careful not to lose their heads economically and ultimately accepted a payment of £15,000 from the British government to permit the unrestricted development of aviation in this country.

Obviously people of the Wright Brothers' quality are altogether exceptional, but there is a certain sense in which they were typical of the new century, or rather typical of the exceptional men of the twentieth century. Their combination of science and wisdom and engineering and daring into the whole man is reminiscent of the combination of qualities that went to make up a Churchill or an Einstein, rather than of the singleness of mind typified by a Gladstone or a Darwin. The great scientific and engineering advances of the present day are coming from the bringing together of widely different departments of knowledge—for example, the way in which electron microscopy has been used to solve the chemical basis of genetics, or solid-state quantum theory to transform electronic circuits.

Certainly, the progress of aviation since the Wright Brothers has been a history of the successive mobilisation of more and more varieties of knowledge and skill. I have a fine opportunity at the Royal Aircraft Establishment of seeing what a variety of sciences and technologies are playing their part—the R.A.E. is practically a "Cal. Tech." in the scope of work that it does—and we are, of course, well aware how many other things, like the intricacies of company finance and production engineering, play equally essential parts in producing the final result.

2. The Principal Areas of Interaction

The object of this lecture, then, is to isolate one of this multitude of contributory disciplines, namely mathematics, and to analyse what is its contribution and how it makes it. You will say, of course "what are we to count as mathematics?" and, so as not to spend too much time on that, I will answer "any calculations which go beyond the systematic application of formulas of the kind which appear in engineer's handbooks"—which means effectively that we will count "any calculations which make use of mathematical discoveries of the past two hundred years." This amounts to simplifying the discussion of the relationship to the extent of putting it through a high-pass filter with a characteristic frequency of five cycles per millennium!

Now certainly in the Wright Brothers' achievement mathematics in the sense which I have defined was not a contributory factor. Nevertheless, at the same time as the experiments at Kitty Hawk, a number of mathematical investigations were in progress which were going to exercise a great influence on subsequent generations of aircraft.

Firstly, Prandtl was developing his boundary layer theory, which he presented in 1904 as a paper to the International Congress of Mathematicians[2]. This work solved the long-standing mystery of why the classical theory of fluid flows, which neglected viscosity, was normally in complete disagreement with observation, even though the viscosity of the fluid had a small value relative to the disturbance, of the order of the reciprocal of the Reynolds number. At the same time it showed clearly that there must be aerodynamic shapes—those to which the adjective "streamlined" was later applied—for which the classical flow pattern would be closely realised. Deviations from that pattern would occur, in fact, only in a thin boundary layer where the velocity would increase from zero at the surface to the classically predicted value at the edge of the layer. However, this layer would remain attached only to a surface on which there were no pressure gradients large enough to bring the flow inside the layer to a halt and cause the rest to break away from the surface.

I must emphasise that the importance of this discovery that close approximations to the flows calculated by potential theory could be achieved with suitable aerodynamic shapes was not primarily that it made jobs for mathematicians!—but rather that the drag coefficient would necessarily be close to the value predicted by the theory, and that this happened to be zero. So close is it to zero in fact that drag coefficients as low as 0·004 have been obtained on aerofoil sections, while even if one considers a complete lifting airframe, the Britannia at its cruising speed has a drag one-twentieth of that of a cube of the same enclosed volume.

However, the way was now open for the judicious application of potential flow theory to aerodynamics—provided that the dire consequences of separation resulting from too great a surface pressure gradient were duly remembered—and this began very soon to throw up valuable results. Kutta[3] and Blasius[4] and Joukow-

sky[5] and Chaplygin[6] and Lanchester[7] showed how aerofoil lift in two dimensions could be explained on potential theory by supposing that such a circulation was set up as would make the flow leave the trailing edge smoothly; they showed also that the lift would be proportional to the circulation, whose genesis could be explained by the fact that unequal quantities of vorticity would be shed by the boundary layers on the two sides of the aerofoil until the smooth-flow condition was fulfilled. Another result of the theory was that pressure gradients especially around the leading edge would become more adverse as the lift increased, so that an abrupt stall could clearly be explained by boundary layer separation at the leading edge.

The big developments in three-dimensional aerofoil theory followed on naturally from all this, and there are two things I would like to emphasise about them—first the indispensable contribution to them of the concepts created by the nineteenth-century mathematical theory of vortex lines and circulation, and secondly the quite exemplary way in which physical thinking and mathematical analysis were integrated with one another, especially in Prandtl's own papers[8]. These papers were the distillation of nearly ten years' work, only towards the end of which did the final method of presentation in terms of free and bound vortices emerge. By means of these new concepts not only did the theory of the lifting line take precise and quantitative shape, but also the whole groundwork for future developments, such as lifting surface theory, was clearly and explicitly laid.

Returning now to the time of the Wright Brothers' first experiments, I will draw your attention to a mathematical paper[9] in the *Proceedings of the Royal Society* for 1904 on a subject certainly dear to their heart, in which G. H. Bryan, the Professor of Pure and Applied Mathematics in the University College of North Wales, gave the first correct calculation of the condition for longitudinal stability. This paper seems to have existed in almost its final form in early 1903, so that Bryan was perhaps chronologically correct when he wrote: "Experiments in gliding under gravity have always been made with machines not too large to be kept balanced by the skill of the experimenter, and the glides, though undoubtedly successful, have been of short duration. Experiments have invariably stopped short of the performance of continuous flight by a mechanically propelled machine. The problem of artificial flight is hardly likely to be solved until the conditions of longitudinal stability of an aeroplane system have been reduced to a matter of pure mathematical calculation." Professional pride can go too far, and in fact, of course, chronological precedence was not here a case of causal precedence, but still the basic aircraft stability theory, lateral as well as longitudinal, which by 1911 had reached essentially its final form in Professor Bryan's book "Stability in Aviation"[10], was to influence profoundly the form of later generations of aircraft, especially by its reduction of the condition for stability to an algebraic relationship between derivatives that were susceptible to wind-tunnel measurement.

I am afraid that, inevitably, most of this lecture is about aerodynamics, rather than about the other aeronautical sciences that have notably interacted with mathematics; there would not of course be time to cover the whole field, and so, perhaps, it is only fair to my audience if I concentrate on the subjects I know most about! Nevertheless, I will mention at this point what are the other major areas of interaction.

In broad terms they are:—

(*a*) the structural area, where the sheer slogging analysis of the stress offices has had to be supplemented by the methods of mathematical elasticity theory to deal with many matters such as stress concentrations, neutral holes, stress diffusion, buckling and post-buckling theory;

(*b*) the aeroelastic area, where the penalities of an empirical approach to flutter were found to be so costly as to place a high premium on the success of a theoretical approach, and as we know herculean mathematical efforts by certain members of this Society produced an elegant and highly useful solution of the problem of flutter prediction, whose accuracy has gradually been refined over the years;

(*c*) the electromagnetic area, where the enormous improvements of the aviator's lot due to radio navigation and communication, and ground and airborne radars, and recent developments such as the desirability of data being telemetred to ground automatically from experimental and prototype aircraft, so that information is available in the case of accident—all this has exacted ingenious compromises between aerodynamic and electrodynamic demands, which have again and again been aided by the furious generation of solutions of Maxwell's equations;

(*d*) the servomechanical area, where the automatic stabilisation and control of aircraft and missiles, and of sub-systems such as an aircraft's electrical generators, has been guided away from trouble, sometimes with great difficulty, by the application of the mathematical theory of servomechanisms and their stability originated by Nyquist[11].

3. The Modes of Interaction

Thus we see that in most of the major departments of aeronautics, relating to the airflow and the airframe and the interactions between them, and the electrical systems and the mechanical systems and the radio-frequency systems, mathematics has played an important part—and recently I think we can say that it has been playing two important parts.

One of these is the one which I discussed at length in my New York lecture[12]—the rôle of mathematics as a generator of new physical ideas; that is, of ideas which have been originated by mathematical investigation but which later become amenable to almost exclusively physical description, and whose properties, although first derived mathematically[13], become familiar and are commonly described in purely physical

terms. Examples of this mathematically generated kind of physical idea, which I have already mentioned, are trailing vorticity, boundary layer, dynamic stability and Nyquist diagram.

The value of physical ideas in practical work, of course, is their elasticity. Provided that they are sound ideas, such as those thrown up as the genuinely appropriate physical description of the mathematical solution of some well defined class of problem, they usually show a splendid capacity to stand up to distortions of the problem, and indeed to radical changes and complications in its conditions, and still give the right guidance about what needs to be done. In other words, a well designed physical idea has wide elastic limits, and will tolerate being pulled and twisted about, and go on giving good service in suggesting the right experiment, or the way out of such and such a difficulty, or in giving someone a feeling that he is not just dismally accumulating a confused mass of experimental data, but there is some thread running through them which gives them meaning and interest. Naturally, then, these ideas are much in demand, and when we come to a new kind of problem, where we are short of physical ideas because none of the old ones that we are accustomed to seems to give any help in solving it, then we can only hope that someone will come along with a mathematical treatment of some appropriately simplified, although possibly also generalised case, and interpret its solution by introducing a new animal into the zoo of useful aeronautical concepts, preferably a well-behaved beast, which all of us will in due course be able to ride as to the manner born, probably ignoring, if we are not mathematicians, what kinds of technique were used to lick him into shape.

The second main contribution of mathematics is the apparently obvious one, of calculating the actual answer!—but in my lecture on these issues seven years ago I found it necessary to stress that the capacity of mathematics to do *this* should not be over-estimated or over-valued, because the full complications of an engineering problem were outside the power of mathematics to grasp; and that these made the suggestive approximation rather than the definitive value all that could be hoped for.

Recent developments following on the acquisition of high-speed computing machines — developments which really consist of the acquisition of experience in how best to use them—have made important changes in this picture. The production of these machines by British firms dates from 1951, and has increased along an exponential curve, with the aeronautical world in the forefront as purchasers and users, accounting for some 30 per cent of the whole[13].

We must not imagine, of course, that these "electronic brains" are always doing highly advanced mathematics. Their biggest field of use in aeronautics has been structural analysis and design, for example of box-type structures, where their typical job is the solution of, say, fifty simultaneous equations, of the ordinary linear type familiar in school algebra. In many ways one of these machines behaves like a vast room full of hundreds of Brunsvigas, hand-operated by contented, intelligent girls with G.C.E., and co-ordinated efficiently by a well-trained team of supervisors.

When I say this, what I really mean is that the machine is much more similar to this large team of girls than to one Isaac Newton. Speed and capacity are its main assets, and we usually find it performing the same kinds of task as conventional desk machines, but on a larger scale—solving fifty simultaneous equations instead of ten, or solving some differential equation in a hundred different cases instead of in just one. Naturally this makes the solutions at once more useful to a designer, who probably wants to know them for a variety of values of the parameters which he wishes to optimise.

However, an important restriction on *most* of the work so far has been that the differential equations have been ordinary, not partial—there have not been many ∂'s, or, in more physical terms, many problems involving both space and time, or more than one space co-ordinate, and the few exceptions have been equations of very simple form. This means that, for complicated problems with more than one independent variable, the machines have proved useful only in finding so-called "similarity solutions." These are solutions involving the independent variables only in one precise combination, say y^2/x, so that the quantity we are seeking is a function of y^2/x alone. This is a function of only one variable and so can be obtained by solving an ordinary differential equation.

In aerodynamics, an enormous number of similarity solutions to flow problems have been calculated and tabulated by using high-speed computers. These exact solutions for particular cases have then been used as checks in the process of constructing good approximate methods for more general cases. For example, one of the earliest of these compendia of similarity solutions was the monumental work by Kopal[14] on supersonic flow around cones, which has been used ever since to evaluate approximate theories of supersonic flow around pointed bodies of revolution, as well as to give an exact value of the pressure at the nose. In the theory of boundary layers also, including, for example, heat transfer across laminar boundary layers, whole volumes of similarity solutions have been found for particular main-stream and wall conditions, and again used in the construction of methods for more general conditions.

What I have said on this topic is by no means intended to belittle the computations on problems with two independent variables which have been successfully done, notably by the method of characteristics or by the peculiarly named "relaxation" method. Of course the machines do the relaxation now—as the man said when he found the second mistake in his programme at midnight only ninety minutes before he was due on the machine. And indeed it is hard work getting one of these more complicated problems out.

From all this you will see why electronic computers have not yet replaced wind tunnels. To calculate even the steady flow around an aircraft one has to solve a

very complicated equation in three space variables. No one has got anywhere near this at all yet, but because it would be so immensely valuable if they could, I shall mention later on some of the more promising steps that have been taken in approximately the right direction. In the meantime I will sum up my remarks on mathematics as a way of getting the actual answer by saying that its limitations in this respect are unquestionably reduced by the work of electronic computers, but that its most powerful use is still in the generation of physical ideas.

4. Slender-body Theory: Scope and History

And now, after that spate of generalisations, I am going to spend the rest of the lecture discussing a particular body of mathematics, together with what it has generated in the way of physical ideas, and of answers, that are of interest in aeronautics. This material, which covers a wide range of subjects, including several of current interest, has come to be called " slender-body theory "—perhaps another of these cases of wishful thinking in nomenclature!

Probably the earliest work in which the ideas of slender-body theory were clearly present was Munk's paper of 1924 entitled " The Aerodynamic Forces on Airship Hulls "[15], where he was able to determine distributions of side force along an airship in steady motion at incidence and in pitch. Munk's ideas were pushed further some twenty years later by his pupil R. T. Jones, in a paper called " Properties of low-aspect-ratio pointed wings at speeds below and above the speed of sound "[18]. This paper showed that lifting-surface theory took on a usefully simple form not only in the limiting case of high aspect ratio, but also for wings of very low aspect ratio, reasonable accuracy being obtained by the simple theory when the aspect ratio was less than one. The paper also recognised, as its title implied, that the lifting surface theory for slender plan forms would take essentially the same form in different ranges of speed—subsonic, transonic and supersonic—which was of course in marked contrast to the situation at high aspect ratio.

Meanwhile in 1932 von Kármán and Moore had written a paper entitled " Resistance of slender bodies moving with supersonic velocities, with special reference to projectiles "[16], and this paper also had been followed by the work of a pupil, H. S. Tsien, on " Supersonic flow over an inclined body of revolution "[17]. These and other papers[23, 19, 20] gradually evolved a slender-body theory for supersonic flow around bodies of revolution.

In 1949 a major synthesis of all this material appeared, in the paper by G. N. Ward on " Supersonic flow past slender pointed bodies"[21], in which the investigations on lifting surfaces and on bodies of revolution, apparently so different, were seen as part of a theory no more complicated than either which applied to slender bodies of arbitrary cross-section, with important applications to wing-body interference. Although the paper confined its attention to supersonic flow, the application to subsonic flow was clearly possible and was made later in Ward's book[22].

This paper showed also that, in steady supersonic flow, the drag of a slender body would depend only on the way its cross-sectional area varied along its length*, and a further conclusion was that the condition for slenderness would be more and more easily fulfilled as the Mach number approached one. These facts probably influenced Whitcomb in his experiments to demonstrate the transonic area rule[24], which later was seen as capable of interpretation within a proper transonic version of slender body theory. Both this transonic version and the hypersonic version involve non-linear equations, but these are at least considerably simpler than the full equations of motion. The main extension to the supersonic version since Ward's work has been Whitham's calculation of the far field[25], including the shape of the various shock waves, which has verified that the calculated supersonic wave drag has the correct relationship to the entropy rise in these shock waves.

The next big advance came from the school of R. T. Jones with Allen and Perkins' paper "A study of effects of viscosity on flow over slender inclined bodies of revolution "[26]. From now on separation effects were firmly incorporated within slender-body theory, and the way was open for the design of a supersonic aircraft that would have the low wave-drag characteristic of a slender shape and would make use of controlled separation to obtain adequate lift at low speed. Controlled separation here means separation from a sharp leading edge, and a large branch of slender-body theory has grown up which deals with the forces associated with the vortices which are shed from that edge.

5. The Main Connecting Ideas

The object of these introductory remarks has been to indicate the scope and history of the theory. Now it is time to describe the main connecting ideas.

The principal idea which runs through the whole theory is that when a body moving through fluid satisfies the slenderness condition—that its surface makes everywhere a small angle with its direction of motion—then the flow in any small region near the body approximates to a two-dimensional flow around a cylinder whose cross-section is the same as the local cross-section of the body (Fig. 1).

I would like to mention at once how similar this is to the theory of wings of high aspect ratio. There also one treats the flow over each wing cross-section as effectively a two-dimensional flow (at a certain angle of incidence) around the local cross-section. There the two-dimensional flows, of which the flow near the surface is made up, are in planes parallel to the direction of motion, but in slender-body theory they are in planes at right angles to the direction of motion.

This analogy is helpful as introducing a second major idea common to both theories. In most cases of high-aspect-ratio wing theory—namely, all those in which the wing develops lift—we can say that " each

*Provided that the rate of change of cross-sectional area was zero at the rear.

FIGURE 1. Flow near cross-section shown approximates to two-dimensional flow around cylinder (broken-line) of same cross-section.

of these local two-dimensional flows takes a specially simple form as one goes away from the surface," and that " in this simple form it becomes part of a big-scale flow," and that " this big-scale flow controls the character of each of the local two-dimensional flows." In fact, the local flow as one goes away from the surface can be regarded as that due to a vortex through the aerodynamic centre, so that the big-scale pattern of flow is that due to a bound vortex of non-uniform strength along the line of aerodynamic centres, together with the free trailing vorticity which this implies. This big-scale flow controls the character of each local two-dimensional flow by fixing its effective angle of incidence.

The great advance which Ward made was in realising that also in most flows around slender bodies—namely, those whose cross-sections have non-zero area—one must regard each local two-dimensional flow around a cross-section as taking a specially simple form away from the surface, where it becomes part of a big-scale flow, which controls the character of each local two-dimensional flow.

However, the specially simple form taken in *this* theory by the two-dimensional flow is not a vortex motion but a source motion (Table I). The source strength is $US'(x)$ per unit length of body, that is, the stream velocity times the rate of change of cross-sectional area with distance. This tending to a simple source motion can be proved mathematically in various ways[21, 27], and the proofs translated into a physical argument, that a change of cross-sectional area pushes fluid aside exactly as if new fluid were being introduced at a volume rate per unit length $US'(x)$, which is the rate of change of cross-sectional area with time as sensed by fluid passing down the body. (For a pulsating body it would be $\partial S/\partial t + U\partial S/\partial x$). Obviously for complicated shapes the effect would be a combination of this source term and various dipoles and higher-order multipoles, but the latter have a small effect far from the surface, compared with the source.

Accordingly, the big-scale flow around a slender body is a line-source flow, not a line-vortex flow, and even for cross-section shapes quite different from the circular there is a tendency, away from the surface, to flow symmetrical about an axis, such as would be produced by a distribution of positive sources where the section is widening and negative sources or " sinks " where it is narrowing. The mathematical character of the big-scale flow is not so different from the line vortex case, since the velocity field of a line source also varies as the reciprocal of the distance (although the directions in the two cases are at right angles).

We come next to how control is exercised by this big-scale flow on the local two-dimensional flows. Here the point to notice is that, as fluid moves over the surface, it is subjected to a disturbance due to a line source of strength $US'(x)$, which is changing at a rate $U^2S''(x)$. The velocity due to the line source varies as

$$\frac{US'(x)}{2\pi r} \quad . \quad . \quad . \quad . \quad (1)$$

where r is the distance from it; and to produce the changes in velocity as the source strength changes a radial pressure gradient

$$\frac{\partial p}{\partial r} = -\frac{\rho U^2 S''(x)}{2\pi r} \quad . \quad . \quad (2)$$

is necessary. Accordingly we have

$$p = -\frac{\rho U^2 S''(x)}{2\pi} \log r + p_0(x) \quad . \quad . \quad (3)$$

in the big-scale flow as we approach the body surface. The variation of pressure takes the form of a logarithmic term, whose coefficient involves the famous $S''(x)$, the second derivative of cross-sectional area with respect

TABLE I

THEORY	Slender-body	Lifting-line
PLANES OF LOCAL TWO-DIMENSIONAL FLOWS	$\perp$ to Stream	$\parallel$ to Stream
SIMPLE FORM OF THESE FLOWS AWAY FROM SURFACE	Line Source	Line Vortex
STRENGTH OF THIS	$US'(x)$ (more generally $\frac{\partial S}{\partial t}+U\frac{\partial S}{\partial x}$),	$\frac{L}{\rho U}$,
WHERE	S is area of cross-section	L is lift per unit span
VELOCITY FIELD	$\frac{US'(x)}{2\pi r}$	$\frac{L/\rho U}{2\pi r}$

to distance x along the surface, together with a constant term as far as r is concerned, namely $p_0(x)$—which can be regarded as a change of static pressure as far as the local two-dimensional flow is concerned, and therefore does not affect the lift on the cross-section, although it can affect the drag.

It is this term $p_0(x)$ which is controlled by the big-scale flow, for which equation (3) represents the behaviour of the pressure as we approach the line source. For the local two-dimensional flow, on the other hand, equation (3) represents the behaviour of the pressure as we get away from the surface towards the region where the flow is practically a source flow. One might say then that equation (3) holds in a region of overlap between the axi-symmetrical big-scale flow and the local two-dimensional flows. The velocity field in the local flow is fixed by the boundary conditions, that is, by the details of changing cross-sectional shape sensed by fluid passing down the body, but the static pressure field for each value of x contains an arbitrary constant $p_0(x)$ which determines how much it differs from the logarithmic term as we go away from the surface and which is, in turn, determined from the big-scale flow—in a manner which is different, as we shall see, in the different speed ranges.

Another main connecting idea, which goes back to Munk[15], is used for the determination of the resultant lift on a cross-section, which as we have seen is independent of $p_0(x)$ and is thus unaffected by the big-scale flow. This idea is based on the fact that the local two-dimensional flow of fluid at right angles to the direction of motion has an effective momentum per unit length, say M. Therefore, fluid as it sweeps past the body with velocity U in the x-direction will have its momentum component at right angles changing at a rate

$$\frac{\partial M}{\partial t}+U\frac{\partial M}{\partial x} \quad . \quad . \quad . \quad (4)$$

per unit length, and the lift force per unit length is equal and opposite:

$$L(x,t)=-\left(\frac{\partial M}{\partial t}+U\frac{\partial M}{\partial x}\right) \quad . \quad . \quad (5)$$

In steady flow the lateral momentum per unit length is a function of x alone, so we simply have

$$L(x)=-U\frac{dM}{dx}, \quad . \quad . \quad (6)$$

giving a total lift $-UM_1$, where M_1 is the value of M at the rear section, that is, the base or the trailing edge.

In other words, the total lift is the rate of shedding of downward momentum at the rear. The motion carrying this downward momentum carries also some energy, say E_1, where E_1 is the value at the rear end of the energy E per unit length of local two-dimensional flows, and is equal to the induced drag.

Another important idea concerns the character of the local two-dimensional flow as fluid sweeping past the body encounters the gradual changes of shape and position of cross-sections. When this flow is set up at the front it is without vorticity, because any flow brought into being instantaneously has this irrotational property. For some flows the irrotational character persists to the rear, and for these the cross flow is particularly simple, depending only on the local shape. For others there is boundary-layer separation in the cross flow, and then the cross flow at rear stations includes vorticity shed at forward stations, which increases the energy E of the cross flow, and usually also its momentum M, above the simple irrotational-flow values.

6. The Big-scale Flow and the Calculation of Wave Drag

I will spend the rest of the lecture looking at some of the particular problems of slender-body theory, beginning with the big-scale flow. This is due to a line source of strength $US'(x)$ per unit length, stretching (say) from $x=0$ to $x=l$, and in steady flow at Mach number M it will have a velocity potential[22]

$$\phi=\left\{\begin{array}{ll} -\dfrac{1}{4\pi}\displaystyle\int_0^l \frac{US'(X)\,dX}{\sqrt{[(x-X)^2+(1-M^2)r^2]}} & (M<1) \\ -\dfrac{1}{2\pi}\displaystyle\int_0^{x-r\sqrt{(M^2-1)}} \frac{US'(X)\,dX}{\sqrt{[(x-X)^2-(M^2-1)r^2]}} & (M>1) \end{array}\right\} \quad (7)$$

where r is the distance from the line source. About these two formulae I want principally to explain why the supersonic is exactly the same as the subsonic, except for an extra factor 2 and a different upper limit in the integral.

To see this we may remember that the whole line source is moving through the fluid, so that for each bit of it we may use the alternative diagrams, so familiar from the textbooks, of a travelling source of sound waves in the subsonic and supersonic cases (Fig. 2). Looking at the subsonic diagram, I have often felt how perplexed a student might well be by the lack of symmetry in this picture, in view of the fact that the pressure distribution of a source is proportional to

$$\frac{1}{\sqrt{[(x-X)^2+(1-M^2)r^2]}} \quad . \quad . \quad (8)$$

(compare equation (7)) in accordance with the Prandtl-Glauert rule, and therefore is symmetrical fore-and-aft about the position of the source. The discrepancy is due to the fact that the gain in wave intensity to the left, where the circles are more crowded together than on the right, is exactly cancelled by a loss due to the relatively greater distance from the point of emission. When the balance of these effects is worked out (see Appendix) one obtains the upper formula in (7), and in the supersonic case the calculation of the integrand gives the same result but, as the diagram shows, a source makes an effect only at points within its Mach cone, to which however it is able to send two separate signals, since each point in this region lies, as we see, on two circles. This explains the extra factor 2 and the restricted range of integration in the lower formula.

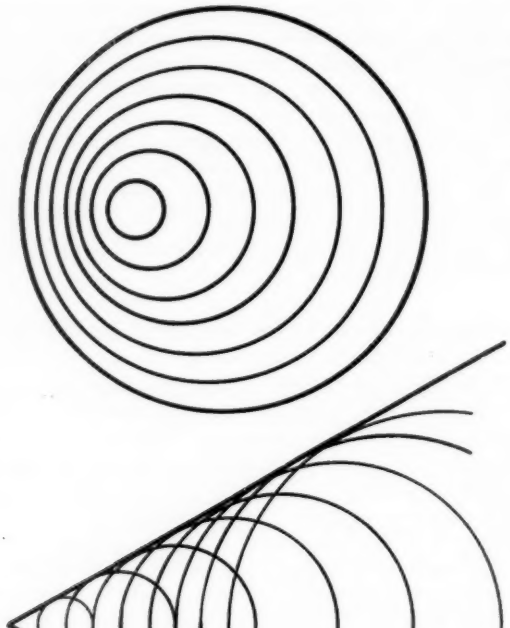


FIGURE 2. Wave pattern of a point source, whose motion to the left is subsonic in the upper diagram and supersonic in the lower.

We may look next at how these expressions for the potential behave as we approach the line source, that is, as $r \longrightarrow 0$. We find that

$$\phi \sim \frac{US'(x)}{2\pi} \log r + \phi_0(x), \quad . \quad . \quad (9)$$

where

$$\phi_0(x) = \begin{cases} -\dfrac{U}{4\pi}\displaystyle\int_0^l \left[\log \frac{2|x-X|}{\sqrt{(1-M^2)}}\right] \operatorname{sgn}(x-X)\, dS'(X) & (M<1) \\ -\dfrac{U}{2\pi}\displaystyle\int_0^x \log \frac{2(x-X)}{\sqrt{(M^2-1)}}\, dS'(X) & (M>1) \end{cases} \quad . \quad . \quad (10)$$

and sgn x is 1 if $x > 0$ and -1 if $x < 0$.

(The corresponding formula was given for the pressure in the general discussion of Section 5, but when one is going into detail for an irrotational flow it is useful to work with velocity potential.) Equations (10) are obtained by integrating equations (7) by parts and approximating the inverse hyperbolic sine or cosine in the two cases by logarithms.

An interesting point is that in subsonic flow these formulae are found to be correct, not only for the bodies with pointed noses that can strictly be regarded as slender, but also for long thin ellipsoids, provided that the source strength is taken as $US'(x)$ only between the foci, with the jump from zero beyond the foci contributing a term to the integral. The same is true of more general round-nosed bodies in subsonic flow if the focus of an osculating ellipsoid is used.

Now, apart from the importance of equation (9) for controlling the static-pressure levels of local two-dimensional flows, it also permits a direct calculation of wave drag D. This uses a formula

$$D = -\rho U \int_0^l \phi_0'(x)\, S'(x)\, dx + \tfrac{1}{2}\rho U \phi_0(l)\, S'(l) - \left(\tfrac{1}{2}\rho \oint \phi \frac{\partial \phi}{\partial n} ds\right)_{x=l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where the last term is an integral round the rear cross-section. The result has been discussed at length from various points of view[21, 28]. One physical interpretation regards it as balancing the work done against drag, DU, by a first term, related to rate of energy transmission through a cylinder surrounding the body, in the region where ϕ is approximately given by equation (9) ($-\rho U \phi_0'$ in this term being a pressure and $US'(x)\,dx$ a volume flow), and the last two together as representing rate of shedding of kinetic energy between the cylinder and the rear cross-section.*

Now, a very common situation at supersonic speeds is for the last two terms to be zero in the position of zero lift because $S'(l) = 0$ and the motion in planes at right angles to the direction of flow vanishes at the rear. (In these cases it would only be at incidence that the last term would make a contribution, namely, the induced drag due to shedding energy in transverse motions at the rear.) Integration of the first term by parts, with use of equation (10), gives at zero lift

$$D = -\frac{\rho U^2}{2\pi} \int_0^l dS'(x) \int_0^x \log(x-X)\, dS'(X), \quad (12)$$

which is usually quoted in the more symmetrical form

$$D = -\frac{\rho U^2}{4\pi} \int_0^l \int_0^l \log|x-X|\, dS'(x)\, dS'(X) \quad (13)$$

In the subsonic case the result is the same except for the sgn $(x-X)$ in the integrand which makes it anti-symmetrical, causing this part of the drag to vanish as it should in subsonic flow.

*More accurately, when $S'(l) \neq 0$, the first rate of energy flow would be smaller by $(\rho U^2/4\pi) S'^2(l) \log r_0$ and the second term greater by the same amount, where r_0 is the radius of the cylinder, but these effects cancel out.

The close similarity of equation (13) to the formula for the induced drag of a lifting line is directly due to the mathematical similarity between the two theories which I remarked on before (Section 5). This means that, just as wing loadings for minimum induced drag can be calculated, so can supersonic area distributions for minimum wave drag. A particularly useful one is the Sears-Haack[29, 30] distribution

$$S(x)=\frac{128V}{3\pi l}\left(\frac{x}{l}-\frac{x^2}{l^2}\right)^{3/2} \quad . \quad (14)$$

giving a minimum wave drag, for a slender body of volume V and length l, with $S'(l)$ zero, equal to

$$D=\tfrac{1}{2}\rho U^2 \, . \, \frac{128}{\pi} \, . \, \frac{V^2}{l^4} \quad . \quad . \quad (15)$$

This is often taken as a standard wave drag for slender bodies of given length and volume, to which observed values can be compared.

It has recently been realised, however[31], that drags below this minimum are obtainable by dropping the restriction $S'(l)=0$. To avoid having zero rate of change of cross-sectional area at the rear, without incurring a base drag, it is necessary to terminate the body at a trailing edge at right angles to the stream. To calculate the drag from the basic slender-body formula (11) one must then include the last term, associated with the energy of the inward-moving cross-flow at the rear cross-section. This flow would need a trailing-edge shock wave to redirect it in the way it should go, but the reduction in dissipation at the front shock due to moving body volume farther back can exceed the increased dissipation in the near portions of the rear shock. For a straight trailing edge we obtain

$$D=\tfrac{1}{2}\rho U^2\Big[\frac{1}{2\pi}\int_0^l\int_0^l \log\left(\frac{l}{|x-X|}\right) S''(x)\,S''(X)\,dxdX - \\ -\frac{S'(l)}{\pi}\int_0^l \log\left(\frac{l}{l-x}\right) S''(x)\,dx + \\ +\frac{S'^2(l)}{2\pi}\left\{\log\frac{l}{(M^2-1)^{\frac{1}{2}}b}+k\right\}\Big], \quad . \quad (16)$$

where b is the trailing edge semi-span and k is a constant which depends on the distribution of trailing-edge angle along the edge, being 1·5 for a uniform distribution and having 1·39 as its minimum possible value*.

The gains achieved are illustrated in Fig. 3 for a delta wing of the shape originally suggested by Squire. The abscissa is the "slenderness parameter" $(M^2-1)^{\frac{1}{2}}b/l$, which relates the degree of sweepback of the leading edge to that of the Mach cone. The ordinate is K_0, a symbol which is used for the ratio of the wave drag to its theoretical minimum for vanishing $S'(l)$. We see that the curve lies below that minimum for slenderness parameters exceeding 0·25, including a substantial range, up to say 0·4, where slender-body theory is found to have good accuracy. The ordinate could be further

*This is $2\log_e 2$, attained for a distribution varying as $(1-y^2/b^2)^{-1/2}$.

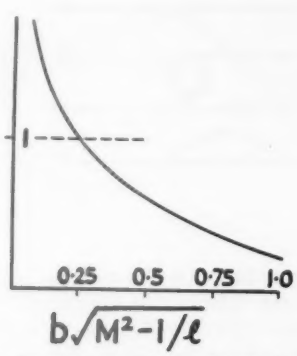


FIGURE 3. Ratio K_0 of wave drag at zero lift for the Squire wing[31] to the Sears-Haack value associated with its volume V and length l.

reduced, for the same area distribution, by up to 0·13 if a more favourable trailing-edge-angle distribution was used to bring k down from 1·64 towards 1·4. This is just an indication of what can be achieved.

One further point about wave drag needs to be mentioned, namely, that the theory as so far described exhibits a discontinuity at $M=1$. Obviously a theory that would give the observed continuous transition from zero at subsonic speeds to a typical supersonic wave drag is necessary. Here I would like to point out that the correct equations of such a theory can be written down[32, 33], although they have not yet been satisfactorily solved. The modification required is that the big-scale flow due to the line-source is no longer subject to a purely linear equation

$$(1-M^2)\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}=0, \quad . \quad (17)$$

leading to the Prandtl-Glauert forms of ϕ. When M is near 1 small variations in the coefficient of $\partial^2\phi/\partial x^2$ in (17) become crucial and the next term in that coefficient has to be retained to get a satisfactory approximation:

$$\left(1-M^2-\frac{\gamma+1}{U}\frac{\partial\phi}{\partial x}\right)\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}=0. \quad (18)$$

We require a solution of (18) behaving like (9) as $r\longrightarrow 0$, which determines ϕ_0, and drag for $S'(l)=0$ is then given as

$$D=\rho U\int_0^l S''(x)\,\phi_0(x)\,dx. \quad . \quad . \quad (19)$$

This then is the problem which needs to be solved, and although the calculation has proved difficult if not impossible†, we can at once say that the answer will depend only on the area distribution. But since the slenderness parameter of any configuration becomes small when M is near 1, that is, the lateral extent of the flow begins to exceed that of the body by a large factor, it may be taken that this result of transonic

†Progress is also slow in hypersonic slender-body theory, in which the local two-dimensional flows exhibit compressibility effects, but longitudinal velocity variations are very restricted relative to lateral ones[34, 35].

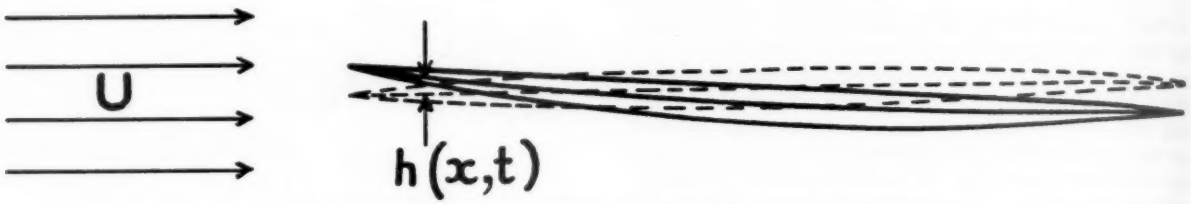


FIGURE 4. Illustrating displacement $h(x, t)$ from straight arrangement.

slender-body theory that wave drag depends only on area distribution is generally valid at transonic speeds, and this of course is the well known and well substantiated transonic area rule.

7. Lift Distributions in Unseparated Flow

The next special problem I want to look at is lift on a slender body, and the way it is distributed along the body in a variety of circumstances, but excluding in the first place those in which separation occurs. For unseparated flows, the momentum of the local two-dimensional motion is rather easily calculated, and the lift distribution deduced from it as described in Section 5. In the meantime in the context of lift a reminder may be appropriate that the term "slender body" includes not only bodies in the conventional sense but also slender wings and wing-body combinations—or "integrations"!

Now, in addition to the steady-flow effects of incidence or longitudinal camber, I want to be able to treat also unsteady pitching motions, both rigid and aeroelastic. To do all this with one theory I shall first distinguish what I call a "straight" arrangement of the cross-sections $S(x)$ in the stream, namely an arrangement in which no cross-section bears any resultant lift, and then allow (Fig. 4) a deviation of the cross-section $S(x)$ from this straight arrangement by an amount $h(x, t)$, the deviation taking place in the z-direction in which lift is to be measured*.

Thus $h(x, t)$ might be independent of time, representing a camber distribution whose lifting effect we wished to calculate, with a term simply $(-\alpha x)$ to represent the effect of incidence α; or else it might include terms due to the camber or the incidence varying with time.

Then the local two-dimensional flows around the body are composed of two parts:

(*i*) those appropriate to the straight arrangement of the cross-sections; and because no lift force acts on any cross-section in this straight arrangement *these* local flows have zero momentum;

(*ii*) those due to the displacement $h(x, t)$ of the cross-section $S(x)$ from this straight arrangement.

Now in the absence of separation this local two-dimensional flow (*ii*) due to the displacements of cross-sections is simply the irrotational flow which would result from the motion of a cylinder of constant cross-section through the fluid at a velocity

$$V(x, t) = \frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x}. \quad . \quad . \quad (20)$$

which is the relative velocity in the z-direction between a cross-section and the fluid passing it with velocity U.

Now, in such an irrotational flow resulting from the movement of a cylinder through fluid with velocity V, the fluid momentum is commonly regarded as an effective added momentum to that of the cylinder itself, and therefore as a product of its velocity V with an added or virtual mass associated with the fluid. We can write this added or virtual mass in the form $\rho A(x)$ per unit length of cylinder, where $A(x)$ has the dimensions of area and has values indicated in Table II for different cross-sectional shapes. Thus the fluid momentum per unit length is

$$M = \rho A(x) V(x, t). \quad . \quad . \quad (21)$$

At the same time the fluid kinetic energy per unit length is

$$E = \tfrac{1}{2}\rho A V^2, \quad . \quad . \quad . \quad (22)$$

which actually is a more indisputable statement than (21) because the integral for the energy converges! From (22), however, it follows that the force applied to the fluid to make a change δV in its velocity must be $\rho A \delta V$, so that the flow does at least behave in all physical respects as if (21) were its momentum! In particular, the lift on unit length of body is given by (5).

In steady flow, this becomes $L(x) = -U dM/dx$, and the total lift is

$$L = -UM_1 = -\rho U A_1 V_1 = -\rho U^2 A_1 h_1' \quad . \quad (23)$$

where suffix 1 indicates values at the rear cross-section and in steady flow V is simply $Uh'(x)$. Thus the lift depends only on the virtual mass ρA_1 of the rear cross-section and on the angle of inclination $(-h'_1)$ of the line of cross-sections at the rear to what I have called their straight arrangement.

The induced drag due to energy shed at the rear is

$$E_1 = \tfrac{1}{2}\rho A_1 V_1^2 = \tfrac{1}{2}\rho U^2 A_1 h_1'^2, \quad . \quad . \quad (24)$$

which is equal to the lift multiplied by half the said angle.

For a straight trailing edge A_1 is πb^2 where b is the semi-span, and then (23) and (24) give an induced drag coefficient of C_L^2/π (A.R.), an extremely familiar form which shows that the trailing vorticity must have

*It will also be assumed that the body has symmetry about the xz-plane. Note that effects of deviation in the y-direction, that is, of sideslip and yaw, are not here considered.

TABLE II

Cross-sectional shape	$A(x)$
Circle radius a	πa^2
Ellipse with major axis a perpendicular to stream	πa^2
Flat plate of width $2a$ perpendicular to stream	πa^2
Same flat plate together with cylinder of radius R centrally placed on it	$\pi\,(a^2-R^2+R^4/a^2)$

an elliptical distribution, as can be verified by a calculation of the local flow at the rear cross-section.

The distribution of lift along the body, which is

$$L(x)=\rho U^2\frac{d}{dx}\{-A(x)\,h'(x)\}, \quad . \quad (25)$$

has its maximum where $-A(x)\,h'(x)$ is increasing most rapidly towards its rear value. Accordingly the centre of lift can be pushed forward by means of negative longitudinal camber, which tends to move that increase forwards[36]. The aerodynamic centre, on the other hand, is at the point

$$x=\frac{\int_0^l XA'(X)\,dX}{A(l)}, \quad . \quad . \quad (26)$$

whose position is fixed largely by plan form.

Table II shows us also how $A(x)$ is reduced from its value for a wing by the presence of a central body, which has proved useful as a measure of reduction of lift by wing-body interference[37]. Another interesting point, if we move away from cases with a straight trailing edge, is that an uncambered slender wing whose span narrows towards the rear can be shown to carry no lift at all beyond the point of maximum span, because the trailing vortex sheet causes this part of the wing to behave exactly as if the span remained constant[18, 21, 22].

I want to pass now to an unsteady example, but in spite of the great importance of the aeroelastic studies of slender wings[38] I find them rather too complicated for lecturing purposes and therefore prefer to show here an example of the versatility of the theory, namely, its use to investigate the swimming efficiency of such fish and marine mammals as can properly be called slender[39].

Now, if one of them causes its body to make oscillatory movements $h(x, t)$, the work that it needs to expend against the lift forces

$$L(x,t)=-\left(\frac{\partial M}{\partial t}+U\frac{\partial M}{\partial x}\right) \quad . \quad . \quad (27)$$

is found, after averaging over the swimming cycle, to have the value

$$\overline{W}=\overline{\left(\frac{\partial h}{\partial t}\right)_1\rho U A_1 V_1}, \quad . \quad . \quad (28)$$

which can be interpreted physically as the average value of the product of the lateral velocity of the tail with the rate of shedding of lateral momentum from it.

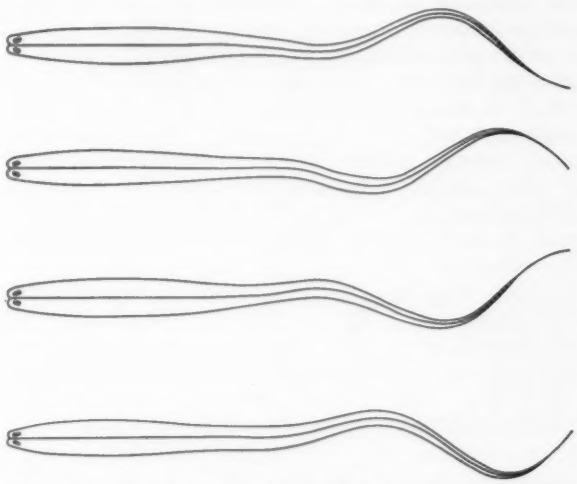


FIGURE 5. Suggested cycle of swimming movements, with time increasing downwards.

Now, of this work done by the fish, an amount equal to the mean rate of shedding of energy at the tail,

$$U\overline{E}_1=\tfrac{1}{2}\rho U A_1\overline{V}_1^2 \quad . \quad . \quad . \quad (29)$$

is wasted, and only the rest goes into producing thrust available for overcoming frictional drag. The fish's problem, then, is to make the tail value of $V=\partial h/\partial t+U\partial h/\partial x$ consistently smaller than $\partial h/\partial t$ itself but at the same time positively correlated with it—while the form of $h(x, t)$ is limited by the laws of momentum and angular momentum and some other practical considerations. A solution of these problems which produces adequate thrust with satisfactory efficiency is illustrated in Fig. 5, where a wave shape chosen to avoid excessive angular recoil is propagated down the fish with an amplitude increasing to a maximum at the rear, and a speed of propagation exceeding the desired swimming speed by about a quarter. This is like the action commonly favoured by fish and swimming mammals, and there is independent evidence that they have achieved remarkable propulsive efficiency. Still their technique has millions of years of evolution behind it, so perhaps there is still hope for us.

8. The Accuracy of Slender-body Theory

I want now to discuss the accuracy of slender-body theory. This subject can be approached both mathematically and experimentally, and in practice one needs both these approaches, if only because one can never do every experiment.

I think that I made the first mathematical investigations of the accuracy of slender-body theory, beginning[19] in 1944 as a result of one of those pungent notes by Dr. A. A. Griffith, in which he tore holes in a first draft of my paper on supersonic flow past bodies of revolution. His objection was that this *is* a peculiar kind of perturbation theory, because if ε is a measure of slenderness, say the maximum angle of inclination of

the surface to the stream, then there are radial velocities on the surface of order $U\varepsilon$, and yet the disturbance as a whole depends on the source strength $US'(x)$ and is of order $U\varepsilon^2$, or at most (as a result of the $\log r$ term which I discussed earlier) of order $U\varepsilon^2 \log \varepsilon$—and logarithms vary very slowly anyway! In particular the axial velocity changes were of this smaller order $U\varepsilon^2 \log \varepsilon$, and so it was doubtful whether they would be given accurately by a perturbation theory which might well be neglecting the squares of the radial velocities (or order $U\varepsilon$).

These suggestions led to a number of interesting investigations which showed that the velocity field was not actually in error from this cause, but that the pressure field was. In deducing it from the velocity field by Bernoulli's equation it was necessary to use not the simple small-perturbation form of that equation,

$$p = -\rho U \frac{\partial \phi}{\partial x} \quad . \quad . \quad . \quad (30)$$

but a more accurate form including the squares of lateral velocities,

$$p = -\rho U \frac{\partial \phi}{\partial x} - \tfrac{1}{2}\rho \left\{ \left(\frac{\partial \phi}{\partial y}\right)^2 + \left(\frac{\partial \phi}{\partial z}\right)^2 \right\} . \quad (31)$$

All this can be understood physically from the idea that near the body a local two-dimensional flow is dominant, with its pressure field given by the last term in (31), and with velocities greater than the perturbation velocities associated with the big-scale flow. At the same time, changes in this local flow as fluid passes the body give rise to transient pressures, represented by the first term in equation (31).

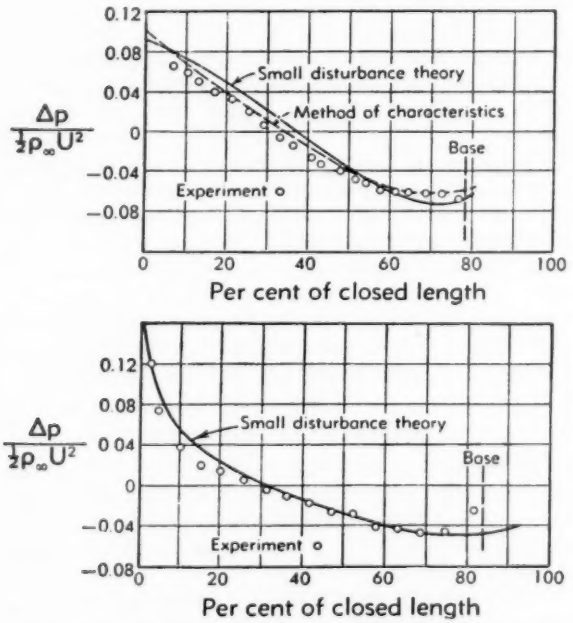


FIGURE 6. Experimental and theoretical pressures over two slender bodies of revolution at $M = 1{\cdot}93$.

Upper body: parabolic profile of length/diameter ratio 11.

Lower body: Sears-Haack profile of length/diameter ratio 12·5. Both bodies are cut off prematurely at a flat base.

The mathematical investigations began with a study of the order of magnitude of the error[19], which was repeated by Ward[21] in his analysis of bodies of general cross-section, and was followed up by explicit calculations of the next approximation for bodies of revolution[40, 41] and more recently for the general slender body[42].

Probably the most important conclusion of these investigations was that the accuracy of slender-body theory depends vitally on the body being not only "slender" but also "smooth." The surface must not make any abrupt changes of direction and in fact the cross-sectional shape must vary gradually all the way from the nose to the rear. Provided that this is so then the percentage errors in the disturbed quantities are of order $\varepsilon^2 \log \varepsilon$. That is, errors in lateral velocities are of order $U\varepsilon^3 \log \varepsilon$, and errors in pressures of order $\rho U^2 \varepsilon^4 (\log \varepsilon)^2$.

This fact, that for slender smooth bodies the relative error is of the order not of the thickness-chord ratio itself but of its square, adds greatly to the usefulness of the theory. At the same time it is often disbelieved, on the argument that in supersonic flow a local change of shape of surface can only affect the flow within its own Mach cone, whereas the theory makes the pressure distribution over any cross-section depend on the shape of the whole cross-section. The fallacy here lies in the concept of a sudden change of surface shape. The smoothness condition requires that any changes be anticipated further upstream and, provided this occurs, then greater accuracy is obtained by using the local shape of cross-section for determining local flow than by any conjectural procedure involving use of upstream shapes.

Another point to notice is that some terms in the relative error involve $M^2\varepsilon^2 \log \varepsilon$ rather than $\varepsilon^2 \log \varepsilon$ itself[42]. This means that for higher supersonic Mach numbers the error becomes greater, unless the slenderness increases so that $M\varepsilon$ remains constant.

To sum up, slender-body theory with its relative error of order $\varepsilon^2 \log \varepsilon$ or $M^2\varepsilon^2 \log \varepsilon$ whichever is the larger,

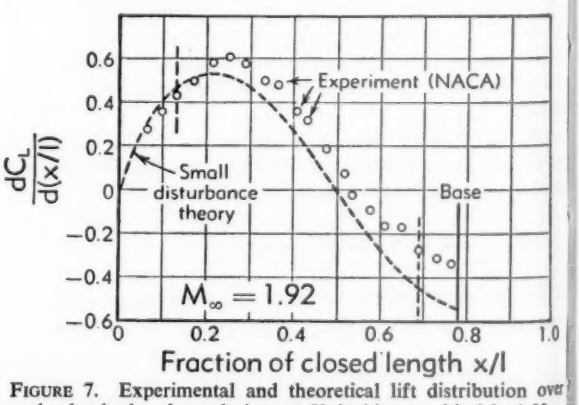
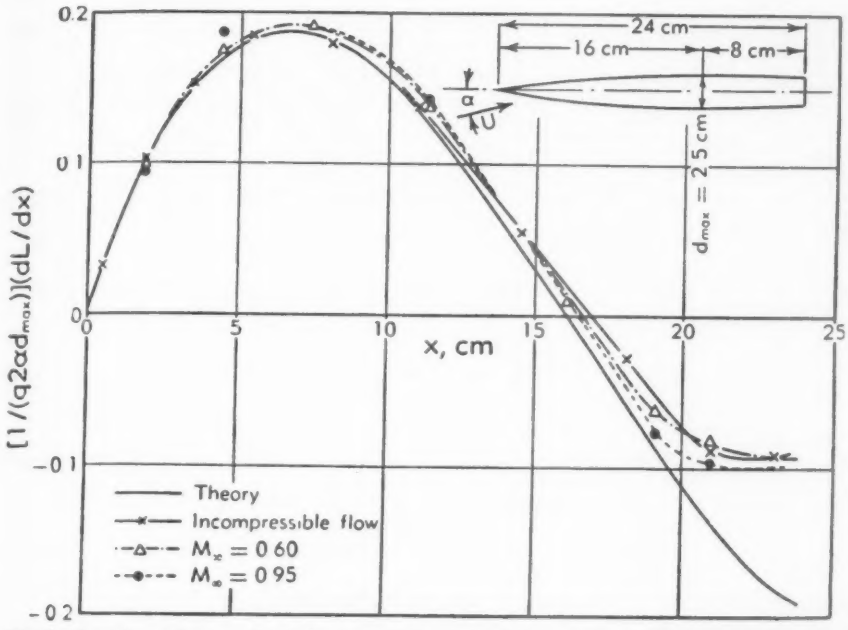


FIGURE 7. Experimental and theoretical lift distribution over slender body of revolution at 5° incidence with $M = 1{\cdot}92$.

Note: Figs. 6 and 7 from C. E. Brown[42]. Section B of *Aerodynamic Components of Aircraft at High Speeds*. A. F. Donovan and H. R. Lawrence (Editors). Princeton University Press. 1957 (O.U.P. London). *Courtesy of Princeton University Press.*



Distribution along the x axis of the normal force coefficient acting on the body having the geometric characteristics depicted, and set at an angle of attack of 3°.

FIGURE 8. Experimental verification of independence of lift distribution on Mach number.

(From C. Ferrari[37]. Section C of *Aerodynamic Components of Aircraft at High Speeds*. A. F. Donovan and H. R. Lawrence (Editors). Princeton University Press, 1957 (O.U.P. London). *Courtesy of Princeton University Press*).

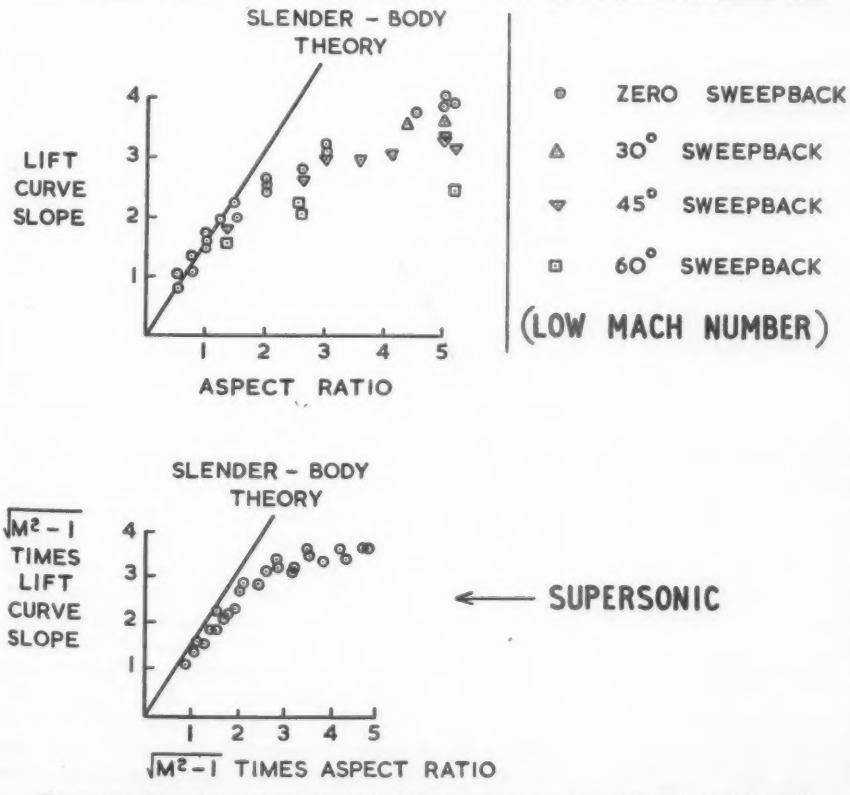


FIGURE 9. Experimental and theoretical lift curve slopes for untapered straight and swept-back wings.

is far more accurate than thin aerofoil theory or thin wing theory, with its relative error of order ε or $M\varepsilon$ for thickness-chord ratio ε.

If I might now begin to substantiate these claims with experimental evidence, Fig. 6 shows pressure measurements[43] on two bodies of revolution in supersonic flow compared with slender-body theory. The maximum angle of the surface to the stream, when multiplied by $\sqrt{(M^2-1)}$ to give a slenderness parameter, is about 0·25 in these two cases. Thin aerofoil theory under these circumstances would be in error by over 20 per cent. Figure 7 shows the lift distribution at 5° yaw over the body to which the upper of these two graphs referred. There is general agreement with the theoretical trend, but the systematic discrepancy results from an additional force due to cross-flow separation which I shall be discussing shortly. Fig. 8 shows that this effect is absent at 3° incidence[37] and supports the theoretical prediction that lift distribution along a slender body is practically independent of Mach number because it is independent of the big-scale flow.

If I may pass to slender wings, Fig. 9 gives a plot[44] of measured lift curve slopes at low speeds against aspect ratio for untapered straight and swept-back wings, which shows already a remarkable tendency to the slender-body theory value below aspect-ratio one, and the lower diagram shows the same effect at supersonic speeds.

Figure 10 supports the idea that at $M=1$, unpromising shapes behave as if slender, by showing that rectangular wings of double wedge section have the lift curve slope predicted by the theory if their aspect ratio is less than the inverse cube root of their thickness-chord ratio[45], in which case also their drag factor K_0 takes a practically constant value, the rather low one 0·25.

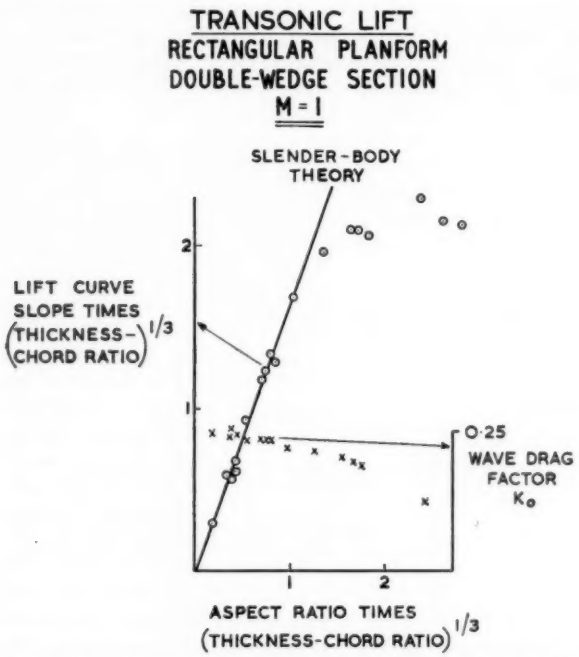


FIGURE 10. Experimental and theoretical lift curve slopes, and observed wave drag factor K_0, at $M=1$.

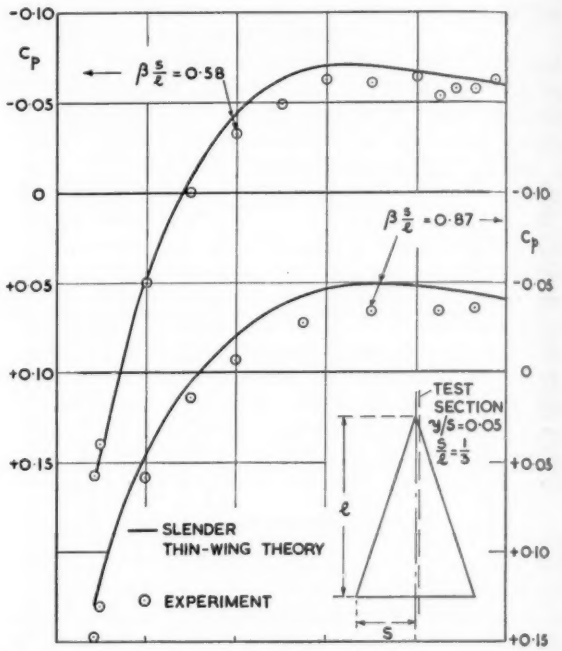


FIGURE 12. Experimental and theoretical pressures along the centre line of a delta wing at zero lift.

At supersonic speeds values of K_0 as low as this are not found, but Fig. 11 shows how values down to 0·5 have been obtained in the R.A.E. 8 ft. tunnel on delta wings with a "Lord V" area distribution and rhombic cross-sections, and how they follow the theoretical curve most peculiarly well up to a slenderness parameter of one. Fig. 12 supports this by giving pressure distributions on a delta wing with rhombic cross-sections. Fig. 13 shows, on the other hand, a definite divergence

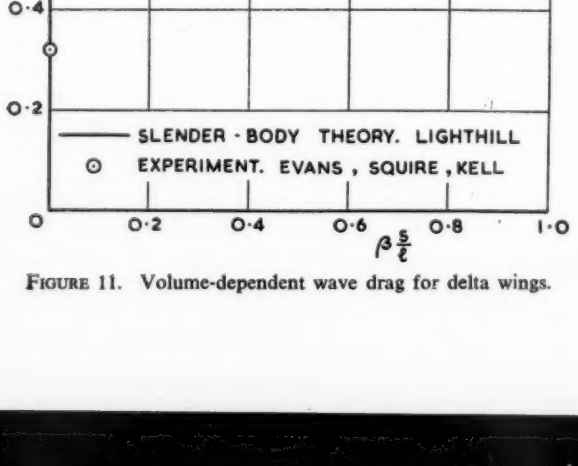


FIGURE 11. Volume-dependent wave drag for delta wings.

of experimental points from theoretical above a slenderness parameter of 0·6.

After this accumulation of evidence that within its sphere slender-body theory does a good job of work, I would like to emphasise again its total inadequacy in cases when the cross-sections exhibit sudden rather than gradual changes with x. Actually a doctored version of it has been constructed which works tolerably for bodies of revolution of this kind[46, 42], but for more general three-dimensional bodies we are still in the dark and interesting attempts to improve the situation by use of high-speed computers by Butler[47] and by Walkden[48] have not yet been really successful.

9. Separated Cross Flows

I will conclude with a brief account of the most recent development in slender-body theory, namely, the extension to the case of separated cross flows which Allen and Perkins initiated with their paper[26] of 1951. They showed for slender bodies of revolution that, although the theory for unseparated flow gives the lift distribution correctly at incidences of two or three degrees, the situation is quite different at higher angles of incidence, when the local two-dimensional flows around the circular cross-sections have separated boundary layers, and the lift is greatly increased as a result.

The basic difference from the unseparated-flow case is that the lateral momentum of fluid passing the cylinder does not simply depend on the local relative velocity V between cross-section and fluid. On the contrary, as the boundary layer sheds more and more vorticity into this cross flow, the cross-flow momentum rises above the unseparated value, at a rate equal to

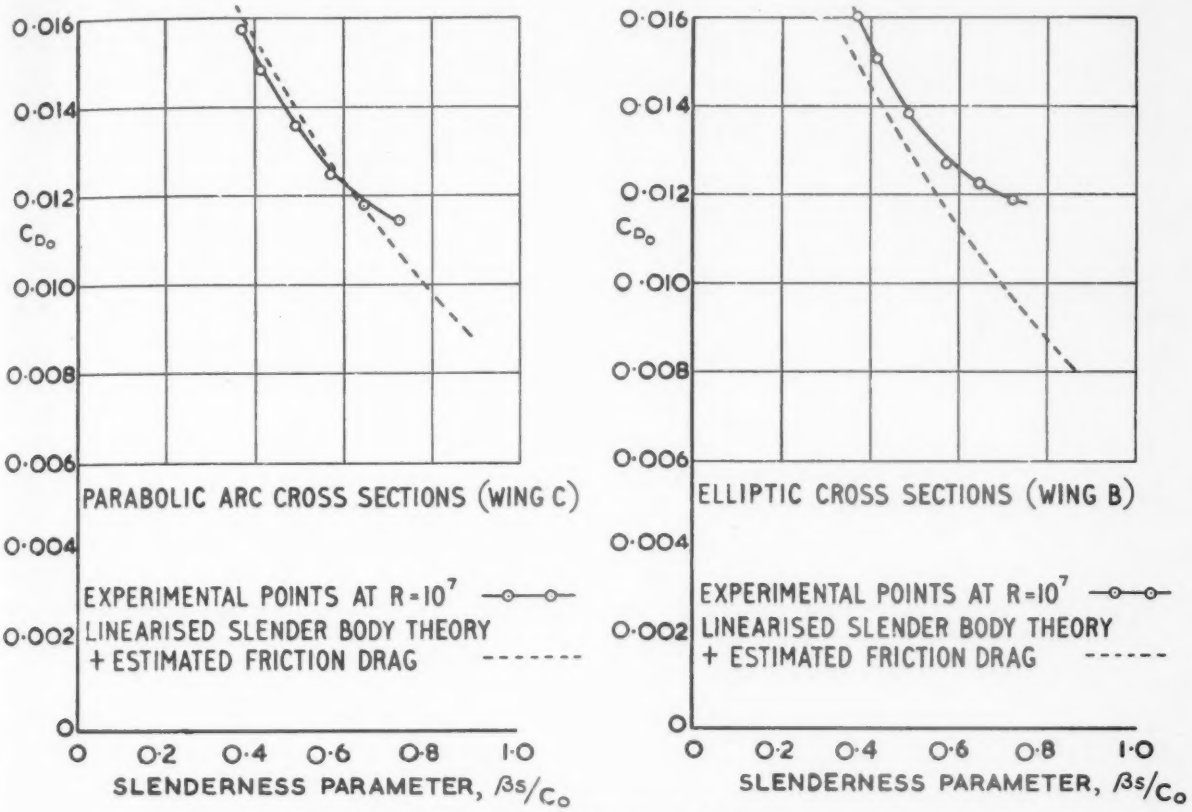


FIGURE 13. The overall zero-lift drag of two delta wings with the same centre section (parabolic arc with thickness-chord ratio 6·75 per cent), but different cross-sectional shapes.

the drag of the cross-section in the separated cross flow, and Allen and Perkins showed that to a good enough approximation this drag may be equated to the drag in steady separated flow past the cross-section.

This implies some simple formulae for aerodynamic forces, such as

$$L=\tfrac{1}{2}\rho U^2\{2S_1\alpha+C_{D\mathrm{cyl}}S_p\alpha^2\}, \qquad (32)$$

which equate the forces to those of unseparated flow plus the effect of an additional cross force on each cross-section equal to the steady-flow drag (with drag coefficient $C_{D\mathrm{cyl}}$) on a cylinder of that cross-section; S_p is the area of the body projected perpendicular to its axis, which sufficiently exceeds the base area S_1 to ensure that the α^2 terms in the lift becomes important for quite small values of α. It should also be noted (Fig. 14) that this quadratic part of the lift acts in a different place, roughly the centroid of this projected area, whereas the linear part acts where the cross-sectional area is most rapidly increasing; and, furthermore, the quadratic part of the lift is inclined to planes perpendicular to the stream at the full angle of incidence α, whereas the linear part is inclined at $\frac{1}{2}\alpha$. Fig. 15 shows that these formulae give a satisfactory account of observed forces—although it

$$L=\tfrac{1}{2}\rho U^2\left(2S_1\alpha+C_{D\mathrm{cyl}}S_p\alpha^2\right)$$

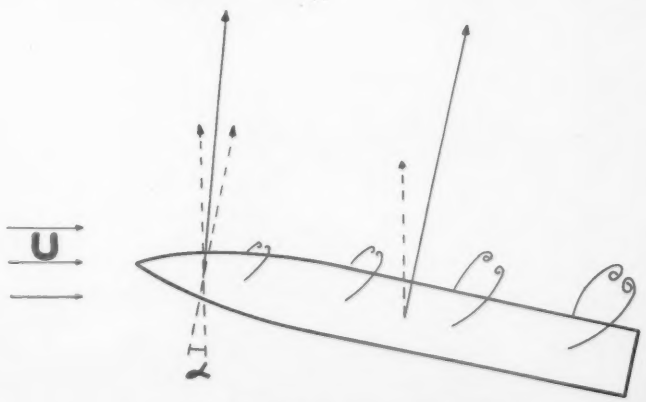
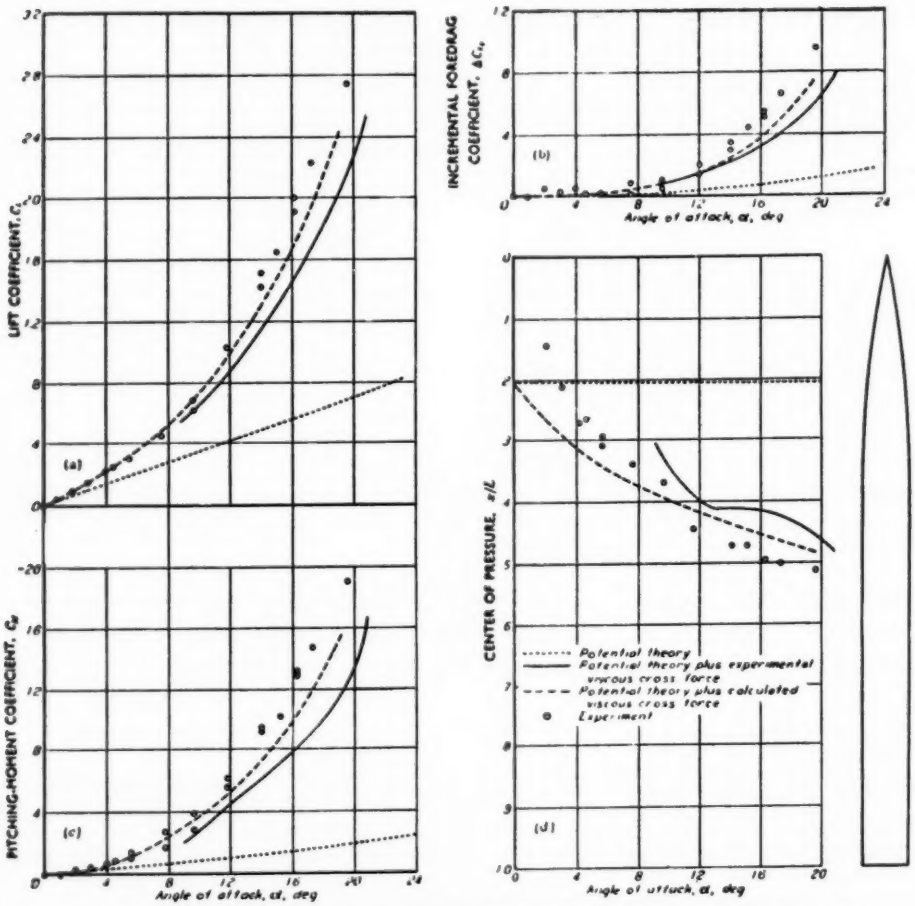


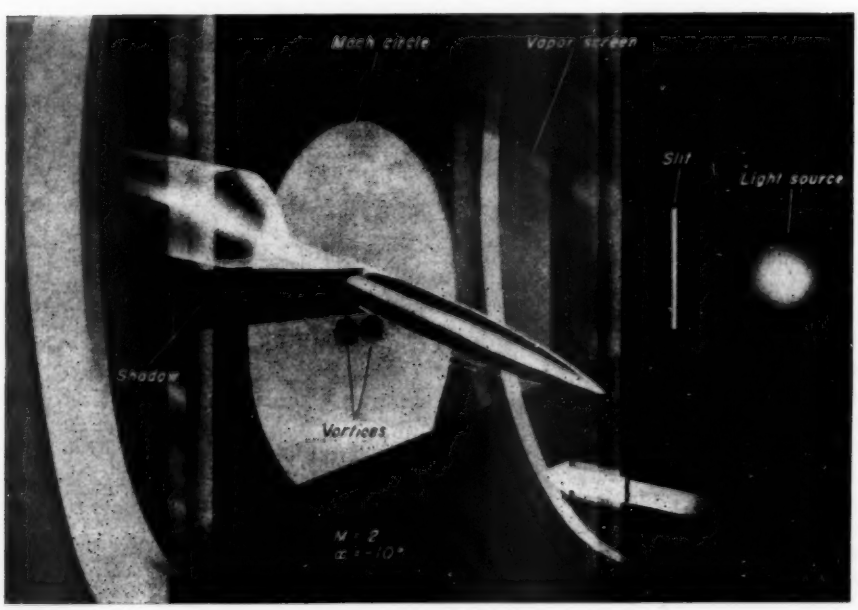
FIGURE 14. Lift from separated cross flows.



FORCE, MOMENT, AND CENTER-OF-PRESSURE CHARACTERISTICS FOR BODY II (FINENESS RATIO 13.1)

FIGURE 15. Allen and Perkins' comparison[26] of their formulae with experimental observations.

(From N.A.C.A. Report 1048, 1951, p. 11).



Schematic diagram of vapour-screen apparatus showing vortices from a lifting body of revolution.

FIGURE 16. Allen and Perkins' method of vortex visualisation.

(From N.A.C.A. Report 1048, 1951, p. 8).

must be admitted that this is partly due to the convenient dependence of C_{Dcyl} on the state of the boundary layer, which means that a value can be picked from within a certain range to give optimum agreement!

The vorticity shed from the boundary layer as the cross flow progresses, builds up into a vortex pair, as Allen and Perkins showed by their vapour-screen method (Fig. 16), and at higher angles of incidence this configuration shows the well-known tendency to asymmetry connected with the beginnings of a Kármán vortex street. This is symptomatic of the severe practical difficulty of using flow separation from a smooth surface to achieve high lifts; one is constantly dogged by the danger of instability and buffeting resulting from the vagaries of the separation position.

This has lead gradually to the concept of "controlled separation," which has now made possible an aerodynamic design capable of attaining the high lift/drag ratio in the "Mach two plus" range characteristic of a slender wing with unseparated cross flow, and of achieving high lift coefficients for landing and take-off with the reliability conferred by vortex production at a fixed edge; namely, at a sharp leading edge[52].

The study of this latter flow régime, which owes much to French work at O.N.E.R.A. during 1951-53[50, 51] would supply enough material for a whole lecture, and mathematical calculations of the vortex configuration and of its implications for aerodynamic forces have again played an important part, being recently brought to a satisfactory state in the steady case by Mangler and Smith[49] and others. The unsteady flow problem for the slender wing with separation at a sharp leading edge remains one of the problems in the field where a sound mathematical treatment would be particularly valuable, but has not been carried out.

As regards the general problem of reconciling aerodynamic requirements in the unseparated-flow régime at "Mach two plus" with those in the low-speed separated-flow régime, I would prefer not to go into details here, but rather to emphasise the importance of a deep understanding of the aerodynamic theory of both flow régimes for appreciating the effect to be expected of different kinds of modification of shape. In this context, I would like to pay tribute to a particular individual, without wishing to appear invidious in any way, or in particular to play down the vital importance of the wind tunnel work which has been done, or of the experimental approach generally. This individual, whose combination of mastery of the mathematical theory and deep physical insight has done so much to mould the test programme into the fruitful directions which it has followed, is Dr. Dietrich Küchemann, and I hope that the contribution which Dr. Küchemann has made and is making towards the creation by these means of a practical economic solution to the problem of the supersonic transport will receive due recognition.

10. Conclusion

Well, Mr. President, that concludes my inadequate effort to illustrate, by a rapid survey of a particular field, the general remarks about the nature of the mathematician's contribution with which I began. I hope at least to have conveyed that he is not an isolationist, and that mathematical calculation is closely and almost inextricably interwoven with physical argument and engineering empiricism throughout its application to the aeronautical field.

I would like to end by some remarks, not about mathematics but about aeronautics. Having been led by the trend of my subject-matter to discuss at last the great project for the introduction of supersonic flight into the civil field, the preparations for which are successfully demanding revolutions in all the branches of the aeronautical art, I may perhaps be permitted to voice some enthusiasm about the new aeronautical age into which we are moving. When I have noted further that this new age will see, also, the widespread use of vertical and short take-off and landing, probably by means of more than one of the subtly contrived methods which are now being so actively studied, and which are giving new life to low speed aerodynamics, and that, yet again, and perhaps most important of all for the common traveller by air, the new age will see automatic landing of aircraft in all weathers, giving reliability and safety to air travel all the year round—and when I have pointed out, finally, that in all these three coming transformations of the aeronautical scene British ingenuity and knowledge and skill are well out in the forefront of all the activity that is going on—then I can only conclude, Mr. President, that all the members of this Society must feel proud of the British aeronautical achievement and confident of its future, and that I must feel proud of having been given the opportunity of addressing you tonight.

APPENDIX

ACOUSTIC-THEORY APPROACH TO THE POTENTIAL OF A LINE SOURCE

We may obtain the potential of a line source, in a stream of velocity U, by regarding the source as moving with velocity U in the opposite direction through fluid at rest and using the formulae of acoustics. If at time $t=0$ the source strength is $U\,S'(x)$ per unit length, then at an earlier time $t<0$ it is

$$U\,S'(x+U\,t)=f(x,t), \text{ say,} \quad . \quad . \quad (1)$$

and the "retarded potential" solution for ϕ at $t=0$ is

$$\phi=-\frac{1}{4\pi}\int_{-\infty}^{\infty}\frac{f\left(X_1,-\frac{\sqrt{[(x-X_1)^2+r^2]}}{a}\right)}{\sqrt{[(x-X_1)^2+r^2]}}\,dX_1$$

$$=-\frac{1}{4\pi}\int_{-\infty}^{\infty}\frac{U\,S'\{X_1-M\sqrt{[(x-X_1)^2+r^2]}\}\,dX_1}{\sqrt{[(x-X_1)^2+r^2]}}, \quad . \quad . \quad . \quad . \quad (2)$$

where a is the speed of sound and $M=U/a$.

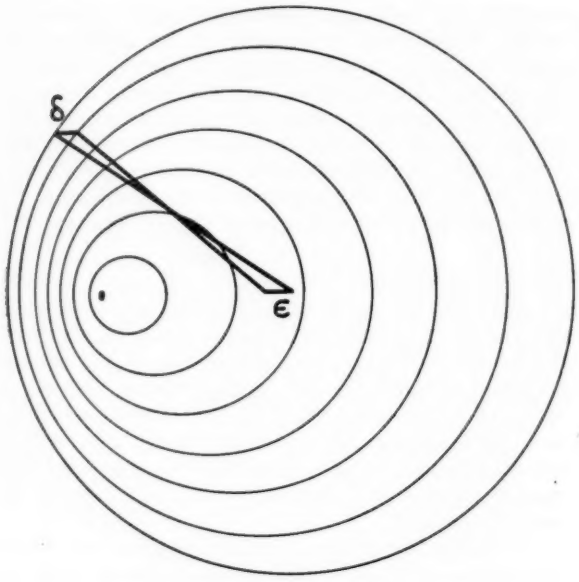


FIGURE 17.

To simplify (2) we make the substitution

$$X = X_1 - M\sqrt{[(x-X_1)^2 + r^2]} \quad . \quad . \quad (3)$$

It is easily calculated that this, as an equation for X_1 (position of the emitting source) given x, r and X (that is, given the "reception" position, at which the potential is being calculated, and the present position of the source) has exactly one solution (with the square root positive) when $M<1$, whereas when $M>1$ it has two solutions for $X<x-r\sqrt{(M^2-1)}$ and otherwise none. Geometrically this corresponds to the fact that the circles in Fig. 2 cover the whole plane once for $M<1$, but cover the Mach cone twice and no other region at all for $M>1$. We also find that in all the cases the solution gives

$$\frac{|dX_1|}{\sqrt{[(x-X_1)^2+r^2]}} = \frac{|dX|}{\sqrt{[(x-X)^2+(1-M^2)r^2]}} \quad . \quad . \quad (4)$$

The deduction of equation (7) of the main paper is now immediate, the extra factor of 2 in the lower formula coming from the fact that each of the two solutions in this case satisfies (4).

The geometry of equation (4) itself is illustrated in Fig. 17. A range δ of horizontal distances between the "reception" point and the present position of the source corresponds to a range $\delta+\varepsilon$ of horizontal distances between the reception point and the position of the source at the time of emission. This fact increases the source strength by a factor $(\delta+\varepsilon)/\delta$, which is greater the more closely the circles are crowded together in Fig. 17. The effect of this factor is modified, as noted in paragraph 6, by variations in the denominator of (2), that is, in the distance to the point of emission; and this gives a final expression symmetrical fore-and-aft about the point $x=X$, as in (4).

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Dr. Moult: The Lecturer had dealt with a difficult subject with great clarity and great skill. It had been an outstanding lecture and he was sure it would go down in the records as one of the best of the Wilbur Wright series. Students of mathematics and aerodynamics of the future, he was sure would read and re-read the lecture in the years to come. A good deal, he must admit, was above his head, but he had enjoyed Mr. Lighthill's philosophising and had fully understood the little bit about the poor fish! It had reminded him of a meeting with Monsieur Coanda many years ago when he had enquired how in the early days of aviation he had discovered his effect. M. Coanda replied, "Well, do you know, I was leaning over a bridge somewhere in France and I observed the trout withstanding the rapidly-flowing stream with only an occasional flip of the tail. I knew that the fish's drag must be much greater than the energy being put out in the flips of the tail and I sought an explanation. This led me to considerations of the important supplementary flows through mouth and gills—which I was later able to demonstrate with an aerofoil in a wind tunnel." Hence "L'effet Coanda."

That was an example of practical observation with subsequent analysis opposed to a mathematical survey with findings to be confirmed later by experiment. There were two approaches and, in aeronautics they needed both.

They had commemorated the fifty-seventh anniversary of flight, but 1960 might be regarded as the Golden Jubilee of British Aviation. Powered flight had started with the Wright Brothers in 1903, but the basic companies and pioneers of flight in this country really got busy in 1910, exactly fifty years ago. It was very appropriate that they should have with them on this occasion Sir Frederick Handley Page, Sir Sydney Camm, and others of those pioneers. He could think of nothing more appropriate than to have given a Gold Medal on the Golden Jubilee of British Aviation to Sir Frederick.

By tradition, there would be no discussion and he would ask Professor Bennett of Cranfield, and a member of Council as Chairman of the Rotorcraft Section, to propose the vote of thanks.

Professor J. A. J. Bennett: This evening when tribute was being paid to the memory of Wilbur Wright, it was perhaps difficult to appreciate how futile mathematics was considered to be, as applied to aeronautics, prior to the development of the first aeroplane. How contrasting the position was today! This thought must have occurred to many members as they listened to Mr. Lighthill's brilliant presentation of the 48th Wilbur Wright Memorial Lecture.

Anything he could possibly say about Mr. Lighthill's ability as an applied mathematician would tend to be an understatement. Mr. Lighthill's recent appointment as Director of the Royal Aircraft Establishment spoke for itself, and, due to his influence, mathematics and aeronautics would no doubt be integrated even more in the future.

To indicate, however, the versatility of their distinguished Lecturer, it might be permissible to mention that he was not only an accomplished pianist, and had composed music, but he was also a classical scholar. This, of course, was not the only reason why he was so much at home with the Greek alphabet!

The name Lighthill in spite of his exposition that evening on slender-body theory, was probably best known internationally as associated with a different aspect of

sound from that of the sonata, namely, the theory underlying the mechanism of jet noise. Thus, if residents near airports continued to send deputations to London to complain about the noise from jet aircraft, it could be expected that Ministerial minds would be well briefed in the future with a complete mathematical explanation! He doubted very much, however, if even Mr. Lighthill would ever be able to brief them adequately on slender-body theory!

In the First Lanchester Memorial Lecture, Dr. von Kármán referred to the 14th Annual Report of this Society where, in 1879, the opinion was expressed: "Mathematics up to the present day has been quite useless to us in regard to flying." The mathematical theory of fluid mechanics had a century previously resulted in the well-known paradox of d'Alembert, to which Mr. Lighthill had referred, the theory having failed to explain the existence of drag. This tended to be typical of the answers expected from mathematics in the early days of Wilbur Wright.

The mathematical approach to aeronautical problems in this country was intensified by Glauert, whose faculty for selecting relevant basic assumptions had rarely been surpassed. Prandtl was, of course, the outstanding aeronautical mathematician of his time and experimental work often confirmed, rather than preceded, the mathematical models that Prandtl conceived.

So many aeronautical scientists had followed in the footsteps of Glauert and Prandtl that aeronautical engineering, to be understood today, required at least a working knowledge of mathematics. One of the greatest difficulties of students who wished to become aeronautical engineers was the mere translation of a problem from the practical language of engineering to the somewhat abstract language of mathematics. There was an urgent need for more emphasis on the teaching of advanced mathematics before specialisation in the main branches of aeronautics. Mr. Lighthill himself had been a pioneer in this respect and, though he might not know it, his professorial influence had extended, at least indirectly, to every student at Cranfield. However, even if mathematical thinking in aeronautics continued to grow as fast as it had done since the days of Wilbur Wright, there was no suggestion that Cranfield might yet become known as "The College of Mathematics and Aeronautics"! Many students considered that it warranted this title even now! Mr. Lighthill's lecture had shown how much a special emphasis on the teaching of mathematics was justified.

He had much pleasure in proposing the vote of thanks to Mr. Lighthill for his inspired lecture.

Following the Lecture a Dinner was given by the President and Council at 4 Hamilton Place at which the following were present:—

Air Cdre. F. R. Banks, C.B., O.B.E., F.R.Ae.S., Hon.F.I.A.S., M.I.Mech.E.; Director, The Blackburn Group Ltd.; Vice President. Mr. A. D. Baxter, M.Eng., F.R.Ae.S., M.I.Mech.E.; Chief Executive, Rockets and Nuclear Energy, de Havilland Engine Co. Ltd.; Member of Council. Wing Cdr. R. P. Beamont, D.S.O., O.B.E., D.F.C., A.R.Ae.S.; Manager of Flight Operations, Chief Test Pilot, English Electric Aviation Ltd.; R. P. Alston Medallist 1960. Professor J. A. J. Bennett, D.Sc., Ph.D., D.I.C., F.R.Ae.S.; Professor of Aerodynamics, College of Aeronautics; Member of Council. Mr. E. C. Bowyer, C.B.E., *Hon. Companion;* Director of the Society of British Aircraft Constructors. Mr. E. G. Broadbent, M.A., F.R.Ae.S.; Senior Principal Scientific Officer, Royal Aircraft Establishment; Wakefield Gold Medallist 1960. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S.; Honorary Treasurer, Royal Aeronautical Society; Member of Council. Sir Aubrey Burke, O.B.E., M.Inst.T., F.R.S.A.; President, Society of British Aircraft Constructors.

Sir Sydney Camm, C.B.E., F.R.Ae.S.; Director and Chief Engineer, Hawker Aircraft Ltd.; Director, Hawker Siddeley Aviation; Past-President and Member of Council. Dr. W. Cawood, C.B., C.B.E., F.R.Ae.S.; Deputy Controller of Aircraft Research and Development, Ministry of Aviation; Member of Council. Mr. R. H. Chaplin, O.B.E., B.Sc.(Eng.), F.R.Ae.S.; Executive Director and Chief Designer, Hawker Aircraft Ltd.; Royal Aeronautical Society Silver Medallist 1960. Mr. A. V. Cleaver, F.R.Ae.S.; Chief Engineer (Rocket Propulsion), Rolls-Royce Ltd.; Member of Council. Dr. R. Cockburn, C.B., O.B.E., Ph.D., A.F.R.Ae.S.; Chief Scientist, Ministry of Aviation; Member of Council. Professor A. R. Collar, M.A., D.Sc., F.R.Ae.S., F.I.A.S.; Professor of Aeronautical Engineering, Bristol University; Vice-President. Mr. J. R. Cownie, B.Sc., Grad.R.Ae.S.; Member of Council. Sir Harold Roxbee Cox, Ph.D., D.I.C., Hon.D.Sc., F.R.Ae.S., F.I.A.S., M.I.Mech.E.; Chairman of the National Council for Technological Awards and Past-President of the Society.

Lord Douglas of Kirtleside, G.C.B., M.C., D.F.C., M.Inst.T., *Hon. Companion;* Chairman, British European Airways. Sir George H. Dowty, Hon.F.C.A.I., F.R.Ae.S.; Chairman and Managing Director, Dowty Group Ltd.; Past-President. Professor W. J. Duncan, C.B.E., F.R.S., F.R.Ae.S.; Professor of Aeronautics and Fluid Mechanics, Glasgow University; Honorary Fellowship 1960.

Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S.; Managing Director, Vickers-Armstrongs (Aircraft) Ltd.; Past-President; Honorary Fellowship 1960.

Sir William S. Farren, C.B., M.B.E., M.A., D.Sc., F.R.S., Hon.F.R.Ae.S., Hon.F.I.A.S., M.I.Mech.E.; Director, A. V. Roe & Co. Ltd.; Director, Hawker Siddeley Aviation Ltd.; Past-President and Member of Council. Mr. L. G. Frise, B.Sc., F.R.Ae.S., A.F.I.A.S.; Director of Special Projects, Blackburn Group Ltd.; Member of Council.

Dr. G. S. Hislop, Ph.D., B.Sc., F.R.Ae.S., M.I.Mech.E.; Director and Chief Engineer, Fairey Aviation Ltd.; Member of Council.

Dr. D. M. A. Leggett, M.A., Ph.D., A.F.R.Ae.S.; Reader in Applied Mathematics, Kings College, University of London; Principal Designate, Battersea College of Technology. Mr. M. J. Lighthill, F.R.S.; Wilbur Wright Lecturer 1960; Director of the Royal Aircraft Establishment.

Mr. P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S.; Immediate Past-President, Royal Aeronautical Society. Colonel Ray W. McDuffee, U.S.A.F.; Assistant Air Attaché, American Embassy. Mr. John A. Miller; N. E. Rowe Medallist (under 21); Hull Technical College. Dr. E. S. Moult, C.B.E., B.Sc., F.R.Ae.S., M.I.Mech.E.; Technical Director, de Havilland Engine Co. Ltd.; President of the Society. Professor A. J. Murphy, M.Sc., F.R.Ae.S., F.I.M.; Principal, College of Aeronautics, Cranfield.

Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S., Hon.M.Inst.T., Hon.A.R.I.B.A.; Chairman and Managing Director, Handley Page Ltd.; Royal Aeronautical Society Gold Medallist 1960. Mr. E. T. Price, Tiltman Langley Ltd. Captain J. L. Pritchard, C.B.E., Hon.F.R.Ae.S., Hon.F.I.A.S.; Secretary, Royal Aeronautical Society 1925/51.

Professor E. J. Richards, O.B.E., M.A., B.Sc., F.R.Ae.S.; Professor of Aeronautical Engineering, Southampton University. Mr. H. G. R. Robinson, B.Sc., A.C.G.I.; Manager of Black Knight Project, Ballistic Missiles Group, R.A.E.; Royal Aeronautical Society Bronze Medallist 1960. Mr. N. E. Rowe, C.B.E., D.I.C., B.Sc., F.R.Ae.S., F.I.A.S., M.I.Mech.E., M.Inst.T., F.C.G.I.; Joint Managing Director, Blackburn Aircraft Ltd.; Member of Council.

Mr. B. S. Shenstone, M.A.Sc., F.R.Ae.S., F.C.A.I., A.F.I.A.S.; Chief Engineer, British European Airways; Member of Council. Air Marshal Sir Herbert D. Spreckley, K.B.E., C.B., F.R.Ae.S., M.I.Mech.E.; Controller of Engineering, Air Ministry; Member of Council. Professor H. B. Squire, M.A., F.R.S., F.R.Ae.S.; Zaharoff Professor of Aviation. Imperial College of Science and Technology. Mr. B. E. Stephenson, F.R.Ae.S.; Director of Engineering, Vickers-Armstrongs (Aircraft) Ltd.; British Gold Medallist 1960.

Mr. W. Tye, O.B.E., B.Sc., F.R.Ae.S.; Chief Technical Officer, Air Registration Board; Member of Council.

Mr. P. A. Wills, C.B.E., A.F.R.Ae.S.; Chairman, British Gliding Association; British Silver Medallist 1960. Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S.; Solicitor to the Royal Aeronautical Society. Mr. T. A. Wolstenholme, A.R.Ae.S.; Group Technical Training Officer, Blackburn Aircraft Ltd; Member of Council.

Professor A. D. Young, M.A., F.R.Ae.S.; Professor of Aeronautical Engineering, Queen Mary College, London University.

Man Powered Flight in 1929

by

ALEXANDER M. LIPPISCH

Alexander Lippisch has spent more than 40 years in aviation and has left permanent marks on almost every aspect of it, but he has completely avoided ordinary aeroplanes.

He first came into prominence as the Technical Director of the Rhoen Rossiten Gesellschaft with his work on sailplane design at the Wasserkuppe from 1920 to the middle 1930's. He lectured to the Society (Vol. XXXV, July 1931) on "The Development, Design and Construction of Sailplanes" and produced a paper of outstanding value to all sailplane designers which was widely read and translated from the English. He designed, among other types of sailplane, the Professor, the Wien, the Falke and the Fafnir I and II. He then devoted himself to the development of the Delta wing, which he invented. In his 1931 lecture he illustrated his Δ-1 as a glider. His tail-less work culminated in the Me-163 tail-less rocket interceptor, the first aircraft to reach 1,000 km./h. (620 m.p.h.) in level flight, when flown by the late Heini Dittmar.

At the end of the War he was studying the problem of the heavily swept Δ and was spirited across to the U.S.A. where he has remained ever since. He is now Research Director for Collins Radio in Cedar Rapids, Iowa, where he has been working for some time on his Aerodyne, a tail-less and wingless deflected jet concept of great technical interest.

Alexander Lippisch also lectured to the Society on "Results from the DFS Smoke Tunnel" (Vol. XLIII, September 1939) in 1939 and showed remarkable slow-motion pictures of air flow, which must have been a revelation to designers.

His activities have embraced the problem of the flapping wing, kites and large-scale (12 ft. span) free-flying research models. He is an inspiring teacher, his teaching being pervaded with a sharp, unexpected gaiety. He has also written numerous papers, including a most useful method for span loading calculation, and has also worked on the problem of man powered flight. He has been most interested in following the efforts of the Man Powered Aircraft Group and is a corresponding member. He has just written the following note on some work he did 31 years ago, which is appropriate and useful even now in connection with our present efforts towards achieving man powered flight.—B.S.S.

THE REVIVAL of interest in flight by man's own muscle power brings back to me some early attempts to solve this problem some 30 years ago.

Needless to say I was—and still am—sold on this idea ever since reading Lilienthal's famous book as a youngster in school. Then came the Wright Brothers and the early years of flying and the years of the First Great War at the end of which I found myself as an Aerodynamicist, designing wing sections and calculating induced drag according to Prandtl's newly discovered wing theory.

The end of the war found us meditating about gliding and the possibility of soaring flight. And so came the Rhoen, and the "Sturm und Drang" of the years on the Wasserkuppe.

When the "Forschungsinstitut of the Rhoen-Rossitten-Gesellschaft" consolidated the efforts of research and scientific progress, there were again here and there people who tried to build man powered aircraft. We should probably not just say aircraft or gliders, since most of these "inventors" had figured out some kind of contraption which, seen from some distance, resembled more one of those prehistoric bird petrifacts. Quite often we were urged to give our expert opinion on such "Pteroptodons."

Usually there was not much to report on these inventions and one often thought how much waste of energy and time was invested in such fruitless endeavour. Would it not be better to give those people the opportunity to come to the Wasserkuppe during the contest and at least to see and learn something which would give them better understanding and opportunity to discuss their opinions. So we started the technical part of the contest and, although it was certainly not a great success, the meetings in the evenings were full of new initiatives.

Among the contestants for this technical event was a medical doctor, Dr. Brustmann, who brought a kind of ornithopter built around and above a bicycle. He did —for his own sake—not get into the air with this vehicle and his ground runs were one of the highlights of amusement, Ursinus running in front with a handkerchief to determine the wind direction and Brustmann high on the wheels flapping the wings like a newly hatched chicken. But Dr. Brustmann had something quite interesting to say.

As a sports physician who trained athletes for Olympic competitions, he had experimented on how to reach a man's highest power output. In the course of this activity he had measured the short-duration power which well trained sportsmen could produce. The figures he gave us regarding the possibility of a muscle-powered aircraft were most encouraging. Today, however, we know from other sources that Dr. Brustmann's figures were quite optimistic.

But the trend of the numbers which he gave me

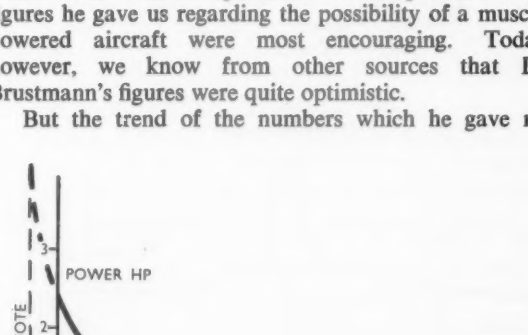


FIGURE 1. The hyperbolic power function according to Dr. Brustmann.

showed that the relation between the human power output and the duration of such effort was a kind of hyperbolic function (Fig. 1). The asymptote for an effort sustained over a long period was in the range of ¼ h.p. The other asymptote was to be placed at a negative time so that for zero duration a figure of 2-2·5 h.p. would result. This relation showed that the human body stored a certain amount of energy which could be expended over a short period, and high power output could be expected for a period of less than one minute. At least I knew that for a short time it seemed actually possible to fly by man's own power, since a lightly built glider plus man would not need more than one h.p. to be flown horizontally.

The discussion of this problem finally led to the plan to build a very light test aircraft to see what we could actually achieve. Since the ornithopter was still favoured in those days, we decided to build such an experimental vehicle as a flapping-wing, man powered aircraft. The reasoning was based primarily on the physiology of the function of muscles which are designed for intermittent use. Besides, it seemed to us that wing flapping would probably have better efficiency and would cause less additional structural weight for the necessary mechanism.

Today I am still inclined to think that wing-flapping actually gives better efficiency, but our knowledge of how to design a highly efficient flapping-wing is very limited and it is certainly easier to use a screw-propeller for propulsion, since we can base our layout on a large variety of experimental work.

It was quite obvious that minimum weight had to be achieved, since for any flying vehicle there is a basic relation between weight, power and lifting surface which states that:

$$\frac{W^3}{\rho \cdot P^2 \cdot S} = \text{dimensionless constant.}$$

where W = weight.
P = power.
S = surface area.
ρ = density of air.

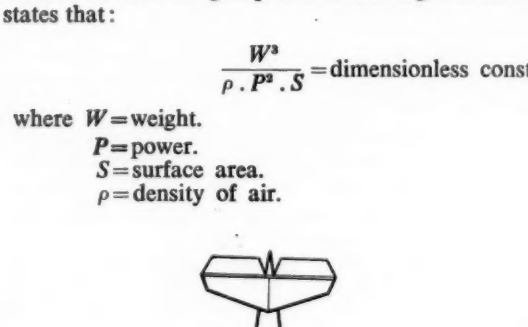


FIGURE 2. Sketch of the plan view of the "Schwinguin." The span was between 9-10 m.

FIGURE 4. Centre view of a wing (inverted position).

Since the design has to strive for a minimum of this "performance number," the influence of saving weight is much more pronounced than that of good aerodynamics.

Most people who think about man powered aircraft today see only the aerodynamic problem. I want to remind these people that the aeroplanes which flew with the lowest power per weight, were the biplanes of the early days.

There is a basic difference between the design of a "minimum power" aircraft and an optimum performance sailplane.

So we decided to build a flapping-wing, man powered craft. I had to design the ship and Alex Schleicher in Poppenhausen was to build it. The main layout is illustrated in Fig. 2. It was a high-wing with open pilot seat and a covered fuselage behind it. The wings were moved by the action of the legs, quite similar to the rowing motion. Each wing had a triangular strut support underneath and on the end of this strut, cables moved the joint in a guide rail fastened to the fuselage. (Fig. 3.)

To compensate the normal lift force, which otherwise would have to be balanced by the force of the pilot's

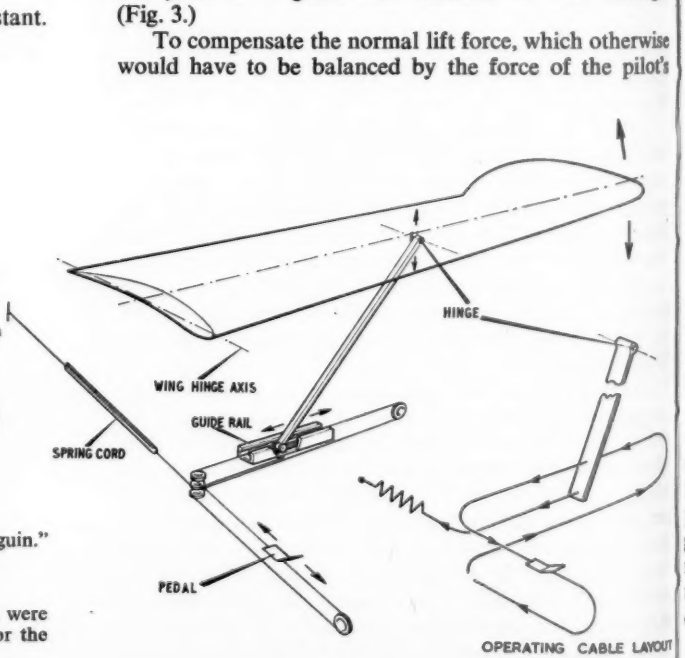


FIGURE 3 (*right*). The wing flapping system. The pullies were attached to a steel tube frame which served as a guide for the movement of the strut joint.

FIGURE 5. Hans Werner Krause after take-off. The height over the ground is obtained from the shock-cord energy.

NB. In both flight pictures the rear extension of the outer wing cannot be seen because this part is flexed upwards.

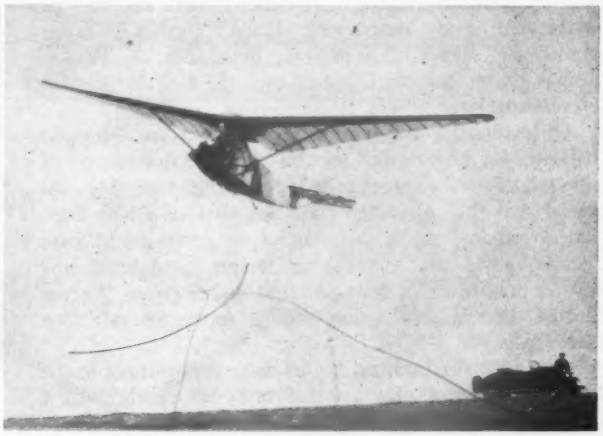


FIGURE 6. The take-off for the "vacation" flight. It is obvious that the crew tried to give Hans Werner as much acceleration as possible. The cable hanging from the rear of the ornithopter was the retainer fastened to the centre frame, since the rear fuselage was not strong enough.

legs, springs (from shock-cord rubber) were located in the rear fuselage. These springs had to be adjusted in such a way that, without any leg force being exerted by the flyer, the aircraft wing would be in a slightly dihedral position in normal gliding flight. The wing structure consisted of a single spar and a very light plywood cover for the nose part and fabric for the rear. The root section was highly cambered and the tip an almost symmetrical section (Fig. 4). The empty weight of this little ship was around 50 kg. This was actually heavier than originally planned since the wing-flapping mechanism with the steel tubing, struts, guide, cables and pulleys took more weight than estimated. Each wing, without the struts attached to it, weighed 4·5 kg. (=10 lb.)

I had further estimated that the thin plywood covering of the nose part of the wings would allow the wing to twist in a downstroke. On the other hand we thought we could expect good propulsive efficiency even without any twisting, due to the Katzmayr effect as measured in a wind tunnel.

As test pilot for this little ornithopter Dr. Brustmann had selected a young pilot, Hans Werner Krause, who was also a good athlete. It must have been spring of 1929 when we began the first test flights.

The control was a stick for elevator and rudder. Sideways movements of the stick gave rudder deflection. There were no wing ailerons because I thought that flapping one wing more than the other would give some lateral control.

The aircraft was launched with a shock cord, which was the usual procedure with gliders. After testing the ship a few times in gliding, Hans Werner tried the first flapping-wing flights. The result was quite disappointing, since we could not see any improvement of the glide angle. At least the effect was so small that the measured Katzmayr effect did not show up, and the twisting of the wings, even with this light construction, did not occur. At first we did not know what to do next.

To find out how to improve things I made some tests with a model wing, and I clearly observed that a stiff wing in flapping motion did not produce any forward thrust. Even turning the wing in its incidence was not sufficient. I then remembered that some of the stories from early years told about a flexible trailing edge. I therefore enlarged the outer portion of the wing by the addition of a flexible (single bamboo sticks) Zanonia-like rear surface as shown in the sketch. This piece was not very large but what a difference in propulsive action was caused by this change!

We tried it first with some flights from the old Weltensegler barracks towards the Pelzner Hang (north-east direction). After a few tests Krause flew all the way to the road, flapping continuously, making eleven flappings for this distance which was in the range of 600 ft. (Fig. 5). An attempt to fly from higher elevation over a larger distance ended in a crash since the lateral control with wings in the lower position was ineffective. We repaired and adjusted more dihedral in the neutral position of the wings.

The main trouble was that Hans Werner did not see any real reason for working hard while flying, since a little engine could have done these things so much better. Such arguments are quite difficult to refute. But there came a rare oportunity in Hans Werner's demand for a vacation to Berlin to see his sweetheart. Well, I said, you can have your vacation if you fly the ship over a horizontal course and a pre-determined distance, which we will lay out. After some arguments about muscle power and too much work we entered a gentleman's agreement on these terms.

The place of action was the little airfield on top of the Pelzner Hang and the distance and the goal were marked by a small puddle which had to be crossed at the end of the flight. (The distance was between 250 and 300 m.).

This flight was accomplished on the first attempt. The crew which stretched the shock cord for the take-off

gave all the encouraging "Ho-ruck" cheers and to our amazement and amusement Hans Werner Krause crossed the "lake" still in flapping flight (Fig. 6). I think he was on his way to Gersfeld and the railroad station ten minutes later.

Unfortunately the machine was afterwards shipped to Berlin for a show and for the unreasonable reason of a better take-off, a steel tube welded undercarriage was added to the aircraft. It was obvious that such "improvement" made this machine a truly earthbound vehicle, since the increase in weight prohibited any further possibility of man powered flight. (Hans Werner Krause died in an accident with a sports aircraft soon afterwards.)

Since the original test flights were not brought to the final achievement of the initial task, the results which, seen in the light of later experience were quite remarkable, were never published.

From this experience gathered from these early man powered test flights I can conclude that an improved version of such an aircraft would give very interesting results.

Now, what should be improved?

First of all the empty weight of such aircraft must be smaller than the weight we achieved by our first attempt. I know now that this can certainly be done.

In recent years we have tried Balsa wood as material for different parts of aircraft construction. The use of this material has brought remarkable results in weight saving. At first sight it seems that Balsa wood is much too low in strength. But if you consider the fact that such material makes it possible to use larger cross sections for the same strength, you begin to realise that you obtain higher local stiffness and quite often you can replace an actually too-heavy member with a properly dimensioned piece from Balsa wood.

The ornithopter described did move the whole wings up and down. From later experiments with flapping wing models I have learned that a design which has a fixed centre part of the wing mainly for lift and which uses the flapping part only in the outer regions, is more efficient. The propulsive efficiency improves if the mean loading of the flapping wings is decreased. A rotational flapping motion similar to the wing movement of most insects and birds is better than a simple up and down stroke.

The flying ornithopter models have further shown that, due to the intermittent break-away of the tip vortex, performance in gliding is improved by flapping. The non-stationary flow also has the advantage of a reduced boundary layer which does not have time to develop to its full grown strength.

The mechanical efficiency of the power transmission from the legs or the arms of the operator to the wings can be considerably improved. The system with cable and pulleys, as we used it, was not satisfactory. A stiff linkage is probably the answer. The counterbalancing by a spring system to hold the wings in a mean position is advisable. The natural frequency of the wing-spring system should be close to the wing beat required in horizontal flight (around $\frac{1}{2}$ per second). From the evaluation of bird flight measurements*, I found that weight, span and wing flapping frequency per second were related by

$$\sqrt{\left[\frac{W}{(\rho/2)\,b^2}\right]} = n_s \,.\, b.$$

where W = weight.
b = span.
n_s = strokes per second.
ρ = density.

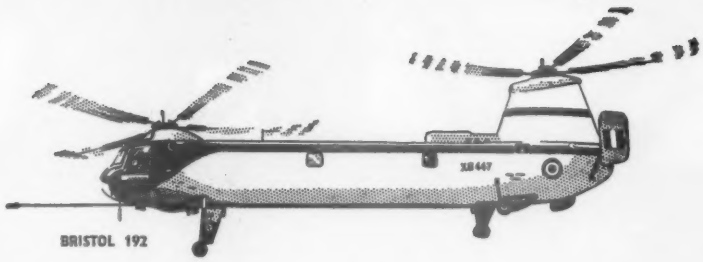
There are some other important characteristics to be taken care of. (Flexible trailing edges in the outer wing or torsional flexibility but stiff in bending!) But I must say again that weight is a dominant factor for the success of such a task.

During the Rhoen years I saw several gliders which had an empty weight of 50 kg. and below. The lightest man-carrying glider was Pelzner's Hangglider of 1922 with a weight of 9 kg. And at that time we did not have the light-weight materials which are available today.

And now I wish much success to my old friends and those younger ones of whom I have heard. Good Luck and "Hals- und Beinbruch"!

*See *Der Biologe IX*, Jahrjang 1940, Heft 5, Die Gesetzmässigkeiten des Vogelfluges. A. M. Lippisch.

SAUNDERS-ROE SKEETER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From the Second Annual Report of the Aeronautical Society of Great Britain 1867.

The Annual Reports of the Society for 1866 - 1893 and the early volumes of the AERONAUTICAL JOURNAL have been virtually unobtainable for some years. With the full co-operation of the Society a facsimile reprint is now available of the 23 Annual Reports 1866 - 1893 in 4 volumes, price £50, and of the first 15 volumes of the JOURNAL 1897 - 1911 in 5 volumes, price £67 10s. 0d., from:

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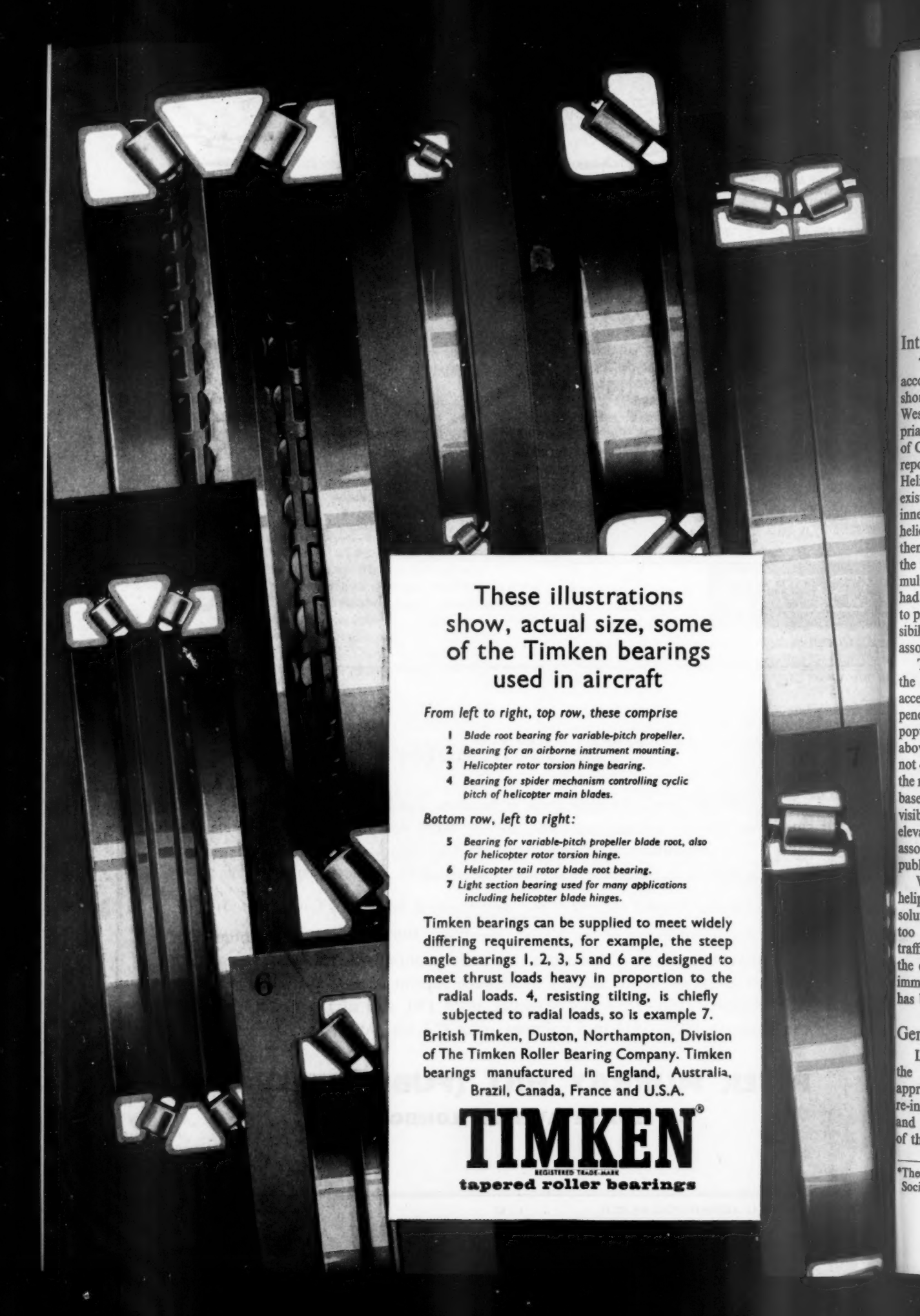

These illustrations show, actual size, some of the Timken bearings used in aircraft

From left to right, top row, these comprise

1. *Blade root bearing for variable-pitch propeller.*
2. *Bearing for an airborne instrument mounting.*
3. *Helicopter rotor torsion hinge bearing.*
4. *Bearing for spider mechanism controlling cyclic pitch of helicopter main blades.*

Bottom row, left to right:

5. *Bearing for variable-pitch propeller blade root, also for helicopter rotor torsion hinge.*
6. *Helicopter tail rotor blade root bearing.*
7. *Light section bearing used for many applications including helicopter blade hinges.*

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Experiences with an Operational Heliport*

by

R. A. C. BRIE, A.F.R.Ae.S.

(Westland Aircraft Ltd.)

Introduction

The subject matter of this paper is primarily an account of operational experience over a comparatively short period resulting from helicopter activities at the Westland London Heliport. At the outset it is appropriate to recall publication by the Helicopter Association of Great Britain, in January, 1958, of a widely circulated report entitled "Examination of the Case for a London Heliport". Therein was expressed the opinion that there existed an immediate need for an operating base in the inner metropolitan area for use by single-engined helicopters. Further, that it was mistaken policy for the then Ministry of Transport and Civil Aviation to relate the need for a London heliport to the future advent of multi-engined helicopters. In the meantime the initiative had been taken by Westland Aircraft as a private venture to provide a suitable site, and to accept financial responsibility for all procedural and constructional work associated with its development and operation.

The first of its kind to be built in this country (Fig. 1), the Westland heliport is also unique in providing an acceptable solution to problems associated with the penetration of single-engined helicopters into the densely populated London area. Mandatory use of the air space above the river Thames between Chiswick and Greenwich not only provides convenient access and exit paths within the regulatory standards of horizontal visibility and cloud base height, but also, a useful navigational aid in poor visibility. Use of the riverway itself by means of an elevated platform successfully overcomes difficulties associated with helicopter take-off performance and public safety requirements.

With a further life expectancy of only five years, this heliport cannot be considered as other than an interim solution to London's permanent heliport problem. It is too small to handle any substantial flow of scheduled traffic, and not quite near enough to the central area for the convenience of the public. On the other hand, the immediate need for the operational facilities it provides has been adequately substantiated.

General Description

Located at Battersea on the south bank of the Thames, the Westland heliport comprises an on-shore area approximately 200 ft. square, and an off-shore T-shaped re-inforced concrete slab platform extending 103 ft. into and over the waterway (Fig. 2). The rectangular head of this 125 ft. long and 53 ft. wide landing and take-off platform is connected to the shore parking area by a 65 ft. wide neck, the whole structure being supported by a system of pre-stressed concrete and steel piles so that the upper surface is flush with a 15 ft. high flood wall forming the shore line boundary. A timber piled fender system along the front, and a part of the upstream and downstream faces, affords protection against damage from water craft navigating the river or berthing at adjoining frontages.

Roughly 70 per cent of the on-shore area is allocated to the surface movement, parking and re-fuelling of helicopters, the remainder being occupied by a low level building with offices for passenger reception and customs clearance, an elevated control tower above a tractor store, and a car park. The overall installation includes essential equipment for fire fighting, land and water rescue, night illumination and so forth.

Although the original conception behind the layout of the parking area has proved in practice to be sound, subsequent systematic expansion in user activity focused attention on the need to provide additional office and stores accommodation. This is being achieved by the erection of a three-section Marley type hut near the entrance gate, and by enclosing the verandah connecting the passenger and control buildings. Thus it is now possible for four permanent resident operators to house their pilot, engineering and traffic staffs, and to be sufficiently self-contained in all matters pertaining to day-to-day activities.

Other improvements to the facilities, to which further reference will be made later, include a platform lighting installation for night flying, additional security arrangements, and a safety net around the perimeter of the landing platform.

Operational Statistics

The Heliport was officially opened on 23rd April, 1959, and a detailed analysis of helicopter usage during the first six months of its existence is recorded in Fig. 3. As for statistical purposes a take-off and a landing rank as two separate movements, there were 650 helicopter landings involved of which 574 were civil and 76 Service users. The busiest month was July, with a total of 356 movements, and the busiest day occurred in September when 30 movements were handled during the Farnborough Show. Over the whole period there was an average of slightly over seven movements each day. Twelve different types of helicopters ranging from small two-seaters to the large Westminster prototype (Fig. 4) have embarked or disembarked 1,751 passengers and 11,064 lb. of freight. Two noteworthy visitors from abroad

*The third lecture given before the Rotorcraft Section of the Society—on 8th April 1960.

FIGURE 1. The Westland Heliport.

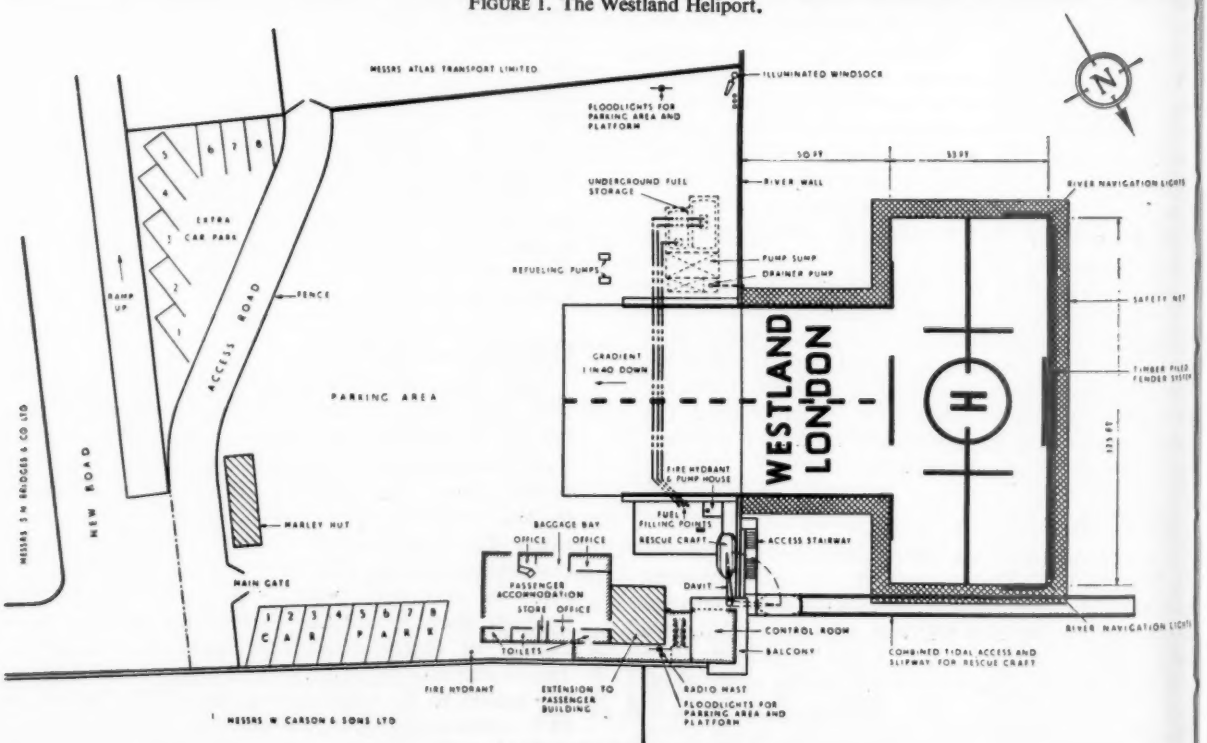


FIGURE 2. Plan of The Heliport.

NATURE OF FLIGHTS	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	TOTAL
COMMERCIAL CHARTERS							
EXECUTIVE & V.I.P.	30	25	42	22	44	61	224
PRESS, PHOTOGRAPHY, FILM, TELEVISION	5	15	25	18	13	10	86
FREIGHT – NEWSPAPERS & GENERAL	11	6	7	5	4	3	36
PRIVATE CIVIL OPERATIONS							
CONSTRUCTORS	2	3	6	1	11	-	23
OPERATORS	3	4	11	8	26	34	86
FOREIGN FLIGHTS	-	-	1	4	1	-	6
POSITIONING & DEMONSTRATION	32	29	66	44	79	18	268
CREW TRAINING, TESTS, TRIALS	1	21①	11	17	10	28②	88
SERVICES & M.O.S.	54	9	26	20	21	22	152
PLEASURE FLIGHTS	8	34	22	46	68	8	186
DAILY MAIL RACE	-	6	138	-	-	-	144
AMBULANCE	-	-	1	-	-	-	1
TOTALS	146	152	356	185	277	184	1,300

① M.T.C.A. Elevated platform trials. ② Platform night lighting trials.

FIGURE 3. Analysis of helicopter movements during first 26 weeks of operation.

were the Sikorsky S.62 and the Vertol 107 helicopters, which were able to demonstrate their amphibious qualities in a characteristic environment.

Heliport Licence

The heliport functions under the terms and conditions of a Ministry of Aviation Private Use Licence. This type of licence is advantageous to the licencee in that notwithstanding the official promulgation of periods during which the heliport is open, actual use by any operator is subject to prior permission being obtained from the heliport controller, and this can be refused without risk of the licence being withdrawn. This "on demand" requirement permits a desirable degree of administrative flexibility in that it ensures adequate staff being available at any given time to meet all contingencies. It also precludes any tendency towards oversaturation of the parking area. As originally issued the licence restricted use to daylight hours and excluded pleasure flying. It has since been amended to permit night flying, subject to weather minima, and a limited amount of daylight pleasure flying.

Heliport Staff

Soon after the heliport was opened it became apparent that the original staff of two salaried air traffic control officers and one general duties employee was inadequate to cope with operational requirements on a regular six-day week basis. Although the normal Monday to Saturday opening period was for 9½ hours each day, *i.e.* 07·30-12·00 and 13·00-18·00, operational requests for facilities during earlier and later hours, and on Sundays, upset preconceived ideas of a systematic duty roster. Hence the early engagement of a second general duties man permitted latitude in arranging staff hours of duty more commensurate with demand.

During the initial exploratory phase of activity when only day-to-day experience could indicate the extent of user requirements, long and irregular periods of staff duty were occasionally inevitable. The air traffic control officers were particularly affected, for in addition to their specialist control duties, they must be responsible for local administration of the heliport. The appointment of the senior of the two officers as Heliport Manager satisfactorily resolved an administrative problem which otherwise might have presented some difficulty. This mutually acceptable arrangement was achieved through the friendly co-operation of International Aeradio, Limited, which organisation provides all A.T.C. staff requirements by contractual arrangement, and has also provided the bulk of the control equipment on a loan basis.

User requirements during the shorter hours of daylight of recent winter months have been less exacting with an average of 3·2 movements a day, and staff duty hours have conformed to normal practice. In anticipation of a near future expansion in the volume of traffic to be handled, steps have been taken to increase the normal hours during which the heliport will be officially open, and to augment staff numbers with an additional controller, one general duties employee, and a telephone operator/receptionist. This will also facilitate early or late extensions of the hours of watch at short notice and will thus carry into effect Westland's policy that, as far as possible, all operational demands shall be met.

Air Traffic Control

As the heliport is in the London Control Zone positive control of helicopter traffic is essential. Hence all helicopters must be able to communicate by radio on the heliport R.T. frequency and, if arriving from, or departing to, the west must also carry the appropriate London Approach frequency. The heliport area of control extends from the Castlenau reporting point, two miles west along the river, to Greenwich in the east.

Helicopters intending to approach the heliport from the west must obtain clearance from London Approach Control and follow recommended routes north or south of London Airport to reach the Thames at Castlenau. Traffic from the south similarly follows a route clear of the prescribed area over which flight by single-engined helicopters is prohibited, before joining the river. For movements from and to the east the Ministry of Aviation has delegated authority to the heliport controller to clear flights through the London Control Zone to Battersea.

Notification by London to the heliport of a helicopter's estimated time of arrival ensures that the landing platform is clear, and the integration of inboard and outboard traffic. The use of a monitor receiver on the London Approach frequency in the heliport tower also assists in this objective.

Despite occasional delays in departure clearance from the heliport during high density movements at the L.A.P., this system functions efficiently with the present small volume of helicopter traffic. On the other hand, the control and integration of helicopter and fixed-wing traffic without unacceptable delays is a problem requiring much thought.

Night Flying Facilities

During the early period of design planning it was foreseen that the installation of night flying facilities could appreciably enhance the heliport's operational value. Hence it was ensured that an adequate mains electrical power supply would be available to meet this and other possible demands as and when the need should arise. In addition, cable ducts to convenient power point plug locations were installed before the heliport was surfaced.

The original licence as issued did not include night flying. This deliberate oversight was advantageous in that it gave sufficient time to all concerned, once the heliport had been opened, to consider the best visual pattern for platform definition and surface illumination. Additionally, the heliport itself was available for *ad hoc* experimentation.

As a result the take-off and landing platform area is now equipped with a simple, but effective, form of night illumination and the licence has been amended to include night flying under defined visual meteorological conditions.

In general, this installation comprises a series of white

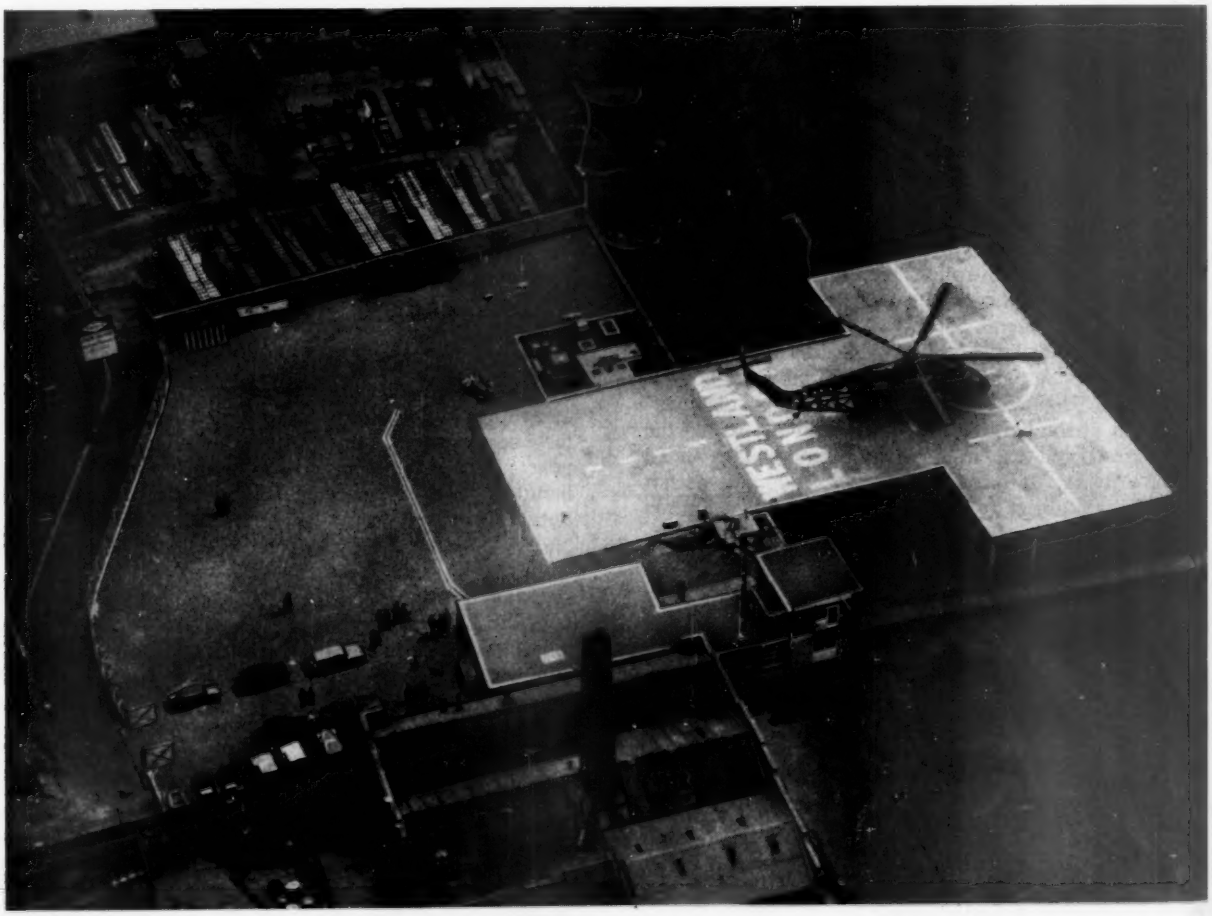


FIGURE 4. Westland Westminster at the Heliport.

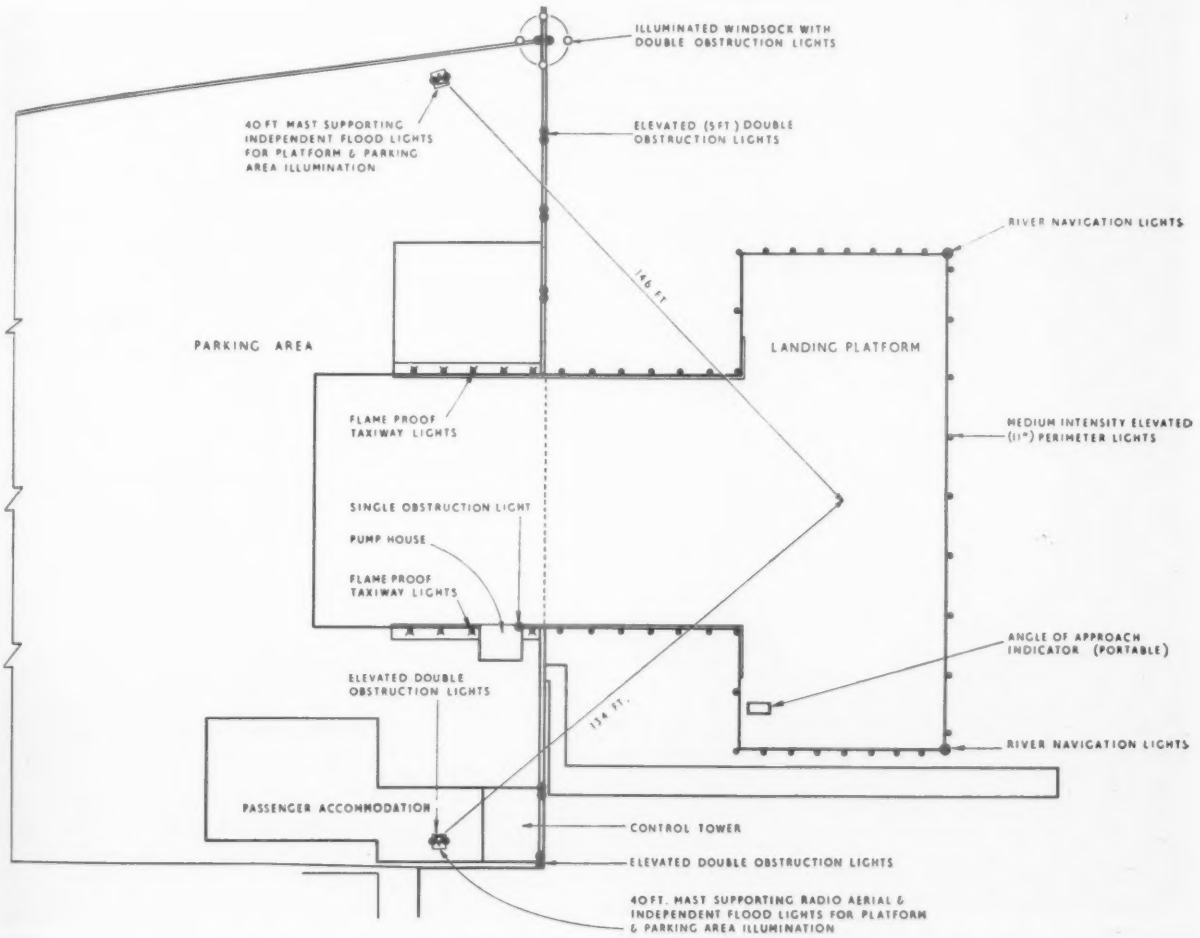

ILLUMINATED WINDSOCK WITH DOUBLE OBSTRUCTION LIGHTS
40 FT MAST SUPPORTING INDEPENDENT FLOOD LIGHTS FOR PLATFORM & PARKING AREA ILLUMINATION
ELEVATED (5FT.) DOUBLE OBSTRUCTION LIGHTS
RIVER NAVIGATION LIGHTS
146 FT.
PARKING AREA
LANDING PLATFORM
FLAME PROOF TAXIWAY LIGHTS
MEDIUM INTENSITY ELEVATED (11") PERIMETER LIGHTS
SINGLE OBSTRUCTION LIGHT
PUMP HOUSE
FLAME PROOF TAXIWAY LIGHTS
ANGLE OF APPROACH INDICATOR (PORTABLE)
ELEVATED DOUBLE OBSTRUCTION LIGHTS
134 FT.
RIVER NAVIGATION LIGHTS
PASSENGER ACCOMMODATION
CONTROL TOWER
ELEVATED DOUBLE OBSTRUCTION LIGHTS
40 FT. MAST SUPPORTING RADIO AERIAL & INDEPENDENT FLOOD LIGHTS FOR PLATFORM & PARKING AREA ILLUMINATION

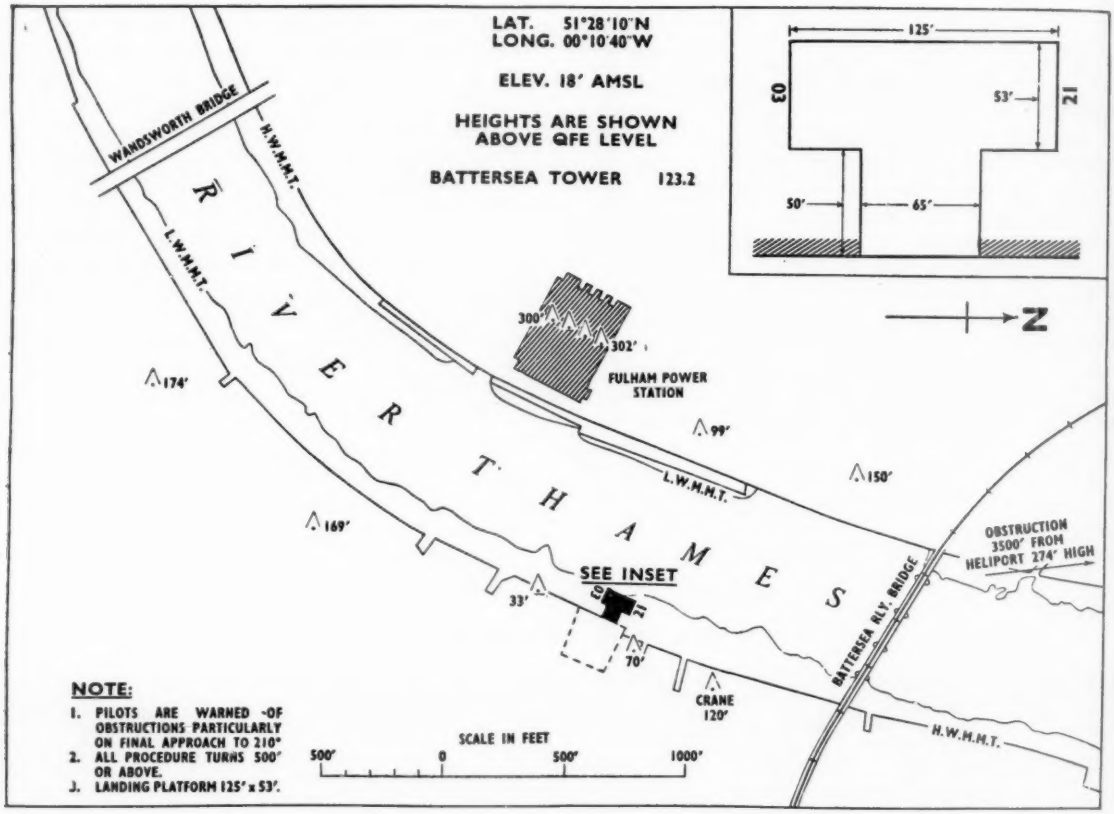
FIGURE 5. Plan of platform lighting.

lights spaced at 15 ft. intervals around the perimeter of the landing platform, and at 7 ft. spacing along each side of the taxiway (Fig. 5). With a maximum output of 300 candelas from each light, the brilliancy can be varied from the control tower according to visibility and to meet pilot requirements.

Platform surface texture lighting is provided by floodlights mounted on two 40 ft. high masts located on opposite sides of the shore area. Each bank of two one kW. lights is able to produce a surface illumination of not less than 0·5 lumens per square foot. Which bank is used is dependent on wind direction, but to minimise any possibility of dazzle to the pilot during the final stages of the approach, or to river traffic, the beams are focused below the horizontal to cut the platform outer edges. It should be noted that the masts also support separately controlled floodlights for illuminating the shore area.

The major axis of the platform which is parallel to the shore-line is aligned in a N.E. - S.W. direction. Under most conditions of wind heading this provides straight-in two-way approach paths, and a tri-colour angle-of-approach indicator (A.A.I.) located along the inner up-wind boundary of the platform enables the pilot to select and maintain a constant 12° angle of descent during the final stages of approach. This A.A.I. unit is portable and interchangeable base socket connections on the platform facilitate its erection in either position according to wind direction.

Fitting obstruction lights to certain industrial buildings and chimneys in the immediate vicinity (Fig. 6) might have presented an installation and economic problem of some magnitude had it not been for a helpful decision on the part of the Ministry of Aviation. Based on the fact that this night lighting installation was in effect an experiment from which much was to be learned, and that it is forbidden for a pilot to overfly the shore, it was decided that purely local shoreline obstruction lighting would suffice. This has been achieved by mounting three groups of two red lights along the southern edge of the river wall, and one red light at each upper outer corner of the control tower, thus effectively delineating the shore line boundary of the obstruction area. Obstruction lighting, together with low density illumination of the wind cone at the south-west corner of the parking area, completed official requirements.



(*Map by courtesy of International Aeradio, Ltd.*)

FIGURE 6. Obstructions in vicinity of the Heliport.

It will be apparent that this night lighting array, the equipment for which was designed by and installed under the supervision of the General Electric Company, is about as simple as could be desired. There is no doubt as to its effectiveness under reasonable visibility conditions (Fig. 7), but only operational experience can determine the extent to which such an installation is adequate to meet the full demands of a commercial heliport. The usefulness of the perimeter lights at full brilliance during poor visibility by day has already been proved.

Customs Facilities

The interior design of the passenger building includes appropriate facilities for handling international traffic. This necessitates the provision of two furnished offices for a Customs and an Immigration Officer respectively, and a segregated area for passenger baggage examination.

Following early discussions with representatives of the Commissioners of Customs and Excise, and H.M. Immigration Office, it became possible to implement basic requirements in such a way as to ensure that when this reserved accommodation was not required, it could be freely used for other more general purposes.

This co-operative and agreeable arrangement is, of course, only officially acceptable so long as demands for Customs clearance are infrequent and of a modest nature. It has permitted a desirable degree of flexibility in the functional design and usage of the passenger building, which is achieved by the use of movable and removable screens, enabling the main passenger handling area to be partitioned as required.

These Customs and Excise facilities, which are available to operators or users subject to reasonable advance notice requirements, have been provided on eight occasions. A recent modest enlargement of the passenger building to provide additional office and passenger handling facilities has necessitated slight positional changes in the Customs area layout, but the ability to reserve the basic accommodation necessary to cover foreign flights is retained.

Security

Although the employment of a night watchman provided reasonable security against unauthorised access during non-operational hours, it soon became evident that the heliport was vulnerable to penetration by small boys from the river approaches and adjoining industrial property. Measures were therefore taken to make such access more difficult by the erection of suitable lengths of metal and barbed wire fencing panels at selected positions on or near the river wall, as well as a locked gate across the steps providing access to the river, or at low tide to the river bed and the slipway for the rescue boat.

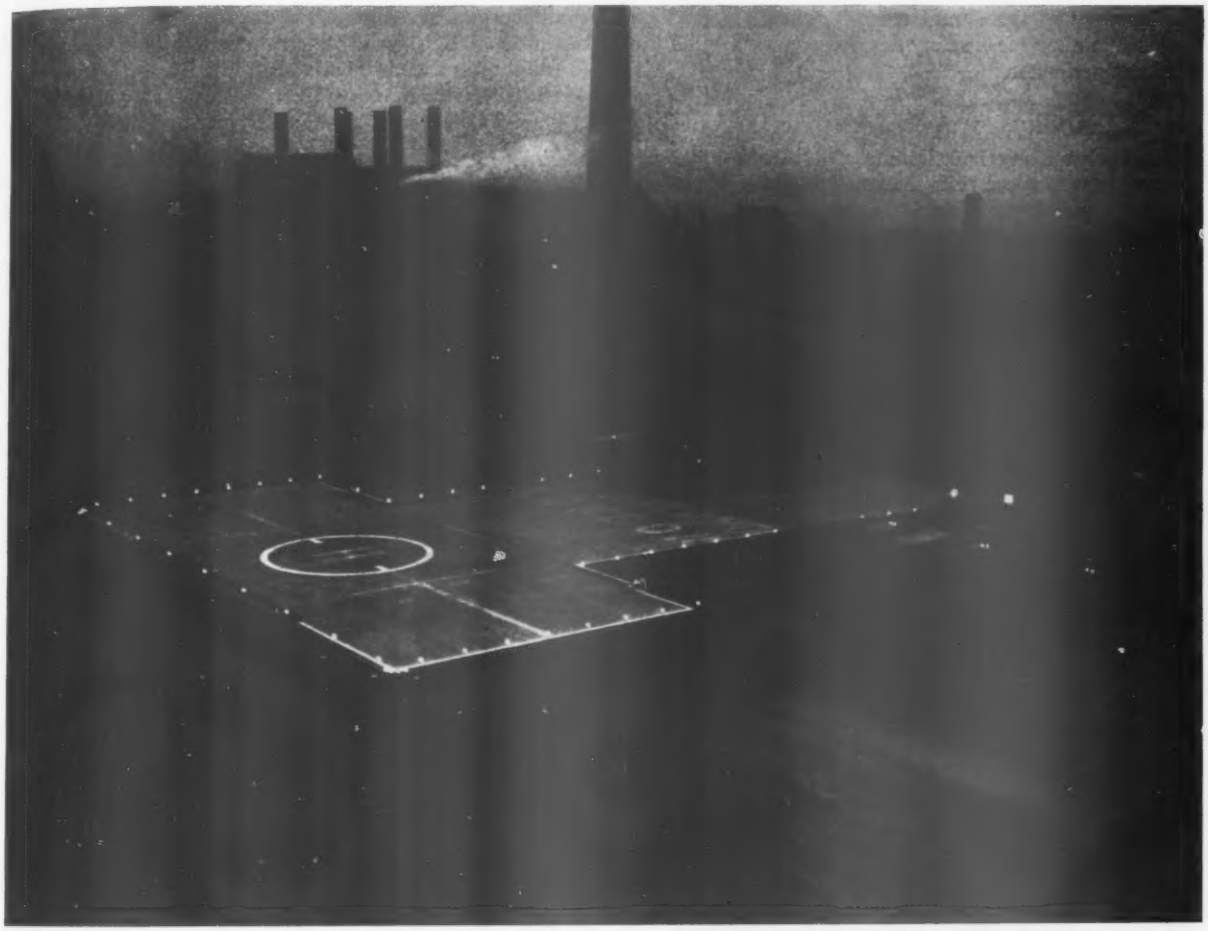


FIGURE 7. Aerial view of platform lighting.

Complete security at an open site is virtually impossible, but these additional precautions at comparatively modest cost have served their purpose.

Safety

The heliport is adequately equipped with a self-contained fire pump to boost the hydrant water supply pressure for foam-producing equipment to combat a localised fire pending arrival within five minutes of the local fire brigade. All staff are trained in fire fighting, rescue and first-aid techniques, and periodic visits from qualified officials, together with spot drills by the Heliport Manager, help to ensure a state of readiness to meet an emergency.

Separate hydrant points providing a water supply at mains pressure are available to wash any spillage of aviation fuel into interceptor drains. The availability of portable fire fighting equipment in the passenger building, sand bins in the parking area, together with rescue and first-aid gear, assists further prompt remedial action in the event of necessity.

Means for river rescue include an outboard-engined inflatable pontoon type of boat capable of carrying ten persons. Slung from a manually-operated davit, this can be lowered into the water or on to a 130 ft. long pile-supported timber slipway at low tide. While light enough to be launched by one or two men over the shingle beach at low water and having desirable water rescue characteristics, handling difficulties in strong winds, and resultant damage to the rubberised fabric structure of this boat against the face of the river wall, are problems to which thought is currently being given.

Two further aspects of safety are associated with helicopter towing and personnel movements. Before the platform was constructed a towing hazard had been foreseen at the corners formed by the junction of the neck with the head of the "T". A satisfactory safeguard against an inadvertent tendency to cut across by a main wheel or a tail wheel is provided by a raised 9 in. concrete plinth. Not quite so obvious initially was the need for similar protection along part of the outer edge of the platform.

Pedestrian movement about the platform also involves an element of risk which it has been considered prudent to anticipate. Although nobody had fallen over the edge, which at low tide is 18 ft. above the exposed river bed,

the hazard was there until recently when a 6 ft. wide aluminium alloy mesh safety net was erected around the platform perimeter.

Legal Liability

By freely making the heliport available for commercial purposes the licencee risks the usual legal liability of an owner of public premises for damages arising from a successful claim involving the use thereof. With the object of limiting such liability some thought was given to the imposition of printed user conditions, but in general this was considered to be impracticable, and all financial risk is covered by insurance.

It was deemed expedient, however, by the conspicuous display of appropriately worded notice boards to warn operators and members of the public against owner risks associated with car parking, hazards from rotors in motion, and from unauthorised access to the flight platform. In addition, pedestrian movement to other than permissible areas is restricted by post and chain barriers.

One particular contingency against which insurance cover has been taken is that associated with the rather remote possibility of vending contaminated fuel and oil.

Economics

Westland has no expectation of any direct financial gain from this experiment, and the measure of success will be a progressive expansion in usage rather than normal commercial considerations. In considering the economic aspects of heliport ownership however, the main source of financial return on the investment must inevitably derive from landing fees. While each landing tends to generate additional sources of revenue from the sale of fuel, and parking fees, these are of a comparatively modest nature.

Landing fee charges at the Westland Heliport at 6/- per 1,000 lb. of maximum certificated all-up weight are on a scale similar to those for fixed-wing aircraft at state controlled airports. It will be apparent for revenue assessment purposes that there exists an important relationship between frequency of landings and the size of helicopters involved. At the present state of the art, however, it must be left to future developments for the beneficial effect of size significantly to affect the financial outlook.

Total capital expenditure, including £7,000 for operational equipment, but excluding A.T.C. equipment, amounts to approximately £80,000. This figure also excludes the cost of the land. Figures for the six months to 31st December 1959 show that the 582 landings during that period incurred a direct operating loss of just over £9 each, after allowing for the above-mentioned sources of revenue and certain notional landing fees. To this must be added depreciation, interest on capital, and administration charges.

A factually accurate picture is thus emerging of the financial aspects of heliport construction and ownership. Staff numbers and the facilities provided are determined by regular and frequent usage, and the scale cannot be adjusted to meet minimum needs. The limited physical dimensions severely restrict manoeuvring and parking, thus making impossible any prospect of full economic utilisation, and profitable operation. On the other hand the results achieved over a comparatively short period cannot be considered altogether unsatisfactory.

Noise

With helicopter activities in a densely populated area it is of major importance that noise should be kept to a tolerable level. Before the opening of the heliport, carefully controlled decibel measurement tests were undertaken at the site with a typical helicopter. These recordings were then compared with similar measurements of noise created by local traffic, industry, and so forth, and the levels were closely comparable.

Day-to-day experience under actual operating conditions has confirmed this assessment, for only two criticisms have been brought to notice. One was associated with night flying tests involving several take-offs, circuits and landings. The other had nothing to do with the heliport, but arose from the slow speed manoeuvres over the city of an aerial photographic charter.

It should be noted, however, that the nearest residential houses are about 500 feet distant, and that the heliport is screened on three sides by industrial buildings. Hence it should not be inferred that so satisfactory a result will follow similar activities at a more centrally located site. On the other hand it is already well established that the gas turbine-engined helicopter can be appreciably quieter than its piston-engined counterpart.

Future Plans

It is Westland policy that all operational users of the heliport shall be entitled without distinction to share its facilities on terms of equality. Limitations in parking space and office accommodation may occasionally necessitate selective action in which case priority will be granted on a "first come first served" basis.

Since the heliport was opened eleven months ago, the volume of traffic handled has exceeded original expectations. Moreover, in anticipation of appreciable user expansion during the coming season, it has been decided further to stimulate utilisation by increasing the daily hours of availability, and to reduce the scale of landing fees to frequent users.

With effect from 10th April, therefore, the normal "on demand" facilities, *i.e.* without additional charge but subject to prior notification of intention to use, will be available for 12 hours daily from Monday to Saturday inclusive, and for 5 hours on Sunday. In effect this means that the heliport will be open for an additional 17½ hours each week. Late evening, early morning, and night operations will also be catered for by special arrangement.

At the same time and to encourage more frequent use, a concession in landing fee charges will become operative. The basic rate for a first landing in any one day will remain at 6/- for each 1,000 lb. of maximum certificated weight, but subsequent landing fees during the same day will be reduced by half, or by a greater amount should advantage be taken of a block arrangement to cover unlimited landings during a specified period.

Conclusion

Despite known limitations in size and location the encouraging nature of user patronage has clearly proved that the Westland Heliport is meeting anticipated operational needs. As a fact-finding experiment devoid of profit motive, but conforming otherwise to normal commercial practice, it is not only producing authentic answers to many problems of an economic and technical nature concerning the operation of a city heliport, but it has stimulated a more general official appreciation and awareness of the rapid approach of the helicopter age, and the associated need for widespread heliport development. Further, it is having the beneficial effect of inducing public interest and acceptability.

Nevertheless, this particular facility is but a short-term, temporary solution to the needs of London, for it would be quite incapable of accepting any sustained high density flow of scheduled traffic such as can be anticipated with future multi-engined passenger transports.

By departing from hitherto accepted conventional standards of site location it has been possible not only to facilitate and control the lawful penetration with safety by single-engined helicopters of a densely populated area, but also to emphasise the operational potential of a waterway. This is a policy the author has been advocating for over twenty years*, and the occasion is opportune to suggest that the River Thames might still hold the key to a practical, economic, and operationally acceptable solution to London's Central Heliport problem.

The provision of at least one centrally located main heliport in London is a matter of national urgency and, whatever its ultimate nature, there is no doubt but that the Westland Heliport will have been instrumental in achieving the major objective for which it was created.

* *The Daily Telegraph*, 25*th February* 1937.

DISCUSSION

The Chairman (N. J. G. Hill, Head, Sales Division, General Precision Systems Ltd., *Associate*): He would like to put the first question to Wing Cdr. Brie with reference to radio navigational aids appropriate to the navigation of helicopters under instrument flight conditions to Heliports of the size and position described in the paper. What were the navigational radio aids under consideration and were any others used than the simple VHF radio telephone?

C. M. Colbeck (Ministry of Aviation, Divisional Controller, Southern Division): They knew that the site on the river was chosen largely to give necessary operational safety for the single-engined helicopter, but they also knew that the multi-engined helicopter was coming before long. That would open up the centre of cities to helicopter operations to a degree not now possible.

Wing Cdr. Brie had referred to an article he had written in the *Daily Telegraph* 23 years previously, in which he had then emphasised the view that water access to the centre of a city was desirable. This was apparently still Wing Cdr. Brie's view and he wondered if there were other factors, apart from the operational requirement of safety for a single-engined helicopter, that made water access or even water near the centre of the city of special value?

Wing Cdr. Brie had mentioned the air traffic control aspects of the operation of the Battersea Heliport. The Ministry of Aviation had watched that with particular interest. Its experience, however, was that there should be no major difficulty in mixing fixed-wing traffic and helicopter operations.

The causes of delay mentioned stemmed largely from the fact that the London Heliport was on one of the direct approaches to a runway at London Airport and that it had been necessary to limit the operating height of the helicopters. But he saw no reason why A.T.C. should not fit rotating wing aircraft into an aerodrome pattern; it would probably present fewer problems than mixing high and low speed fixed-wing aircraft in the approach pattern.

Another interesting aspect was the lighting. He had made the inspection before extending the licence for night operations. The perimeter lighting was very effective and had proved itself in day-time. But he thought that in good weather conditions at night the texture lighting—what Wing Cdr. Brie described as the floodlighting of the platform—would be most useful. He had made several landings without the perimeter lighting on and had found the texture lighting sufficient.

Wing Cdr. Brie had dealt very fairly with the noise question and had pointed out that the lack of complaints might be due to the special situation of the heliport.

Noise was, indeed, a most perplexing problem and for some time to come might be the governing factor in the selection of heliports. Wing Cdr. Brie had pointed out that the gas-turbine-engined helicopter was undoubtedly less noisy than the piston-engined machine. But the noise of the rotor blades would probably never be removed.

Perhaps, until the experts could beat the problem of noise they would have to stay with water access for the helicopter operations into the big cities.

On a more sombre note, there was the question of cost. As Wing Cdr. Brie had pointed out, with a quite modest number of landings the loss per landing was £9. Probably the number of landings could be trebled without increasing direct operating costs. Even so, it seemed that for some time to come there would be a loss on the operation of heliports. He thought that was generally accepted, and that it was right. He had talked to many and the general feeling appeared to be that they were prepared to pay modestly for a heliport, but what perplexed them most of all was the noise.

He was sure everyone appreciated the courage of the Westland Company in developing the London Heliport, the first heliport in the United Kingdom built especially for its special task. Not only had it provided a great deal of individual experience and knowledge, but it would continue to offer practical experience and information on all aspects of heliport operation.

Wing Cdr. Brie: On the question which had been asked by the Chairman as to whether any consideration had yet been given to the installation of what he called instrument approach navigational aids, the answer was "No." They had not as yet been notified of an operational requirement of that extent. On the other hand, they had anticipated that the heliport might be called upon to meet such a re-

quirement during its lifetime, and they had taken care to ensure that, no matter what the nature of those aids might be—radar and so forth—there would be an adequate source of electrical power. If an operator who had need for these facilities or a company which developed such aids wished to carry out experiments, Westland would be willing to collaborate. There were undoubtedly many local problems to be resolved, such as screening and so on.

Mr. Colbeck's first query had to do with some thoughts which he had expressed in the *Daily Telegraph* in 1937 on the value of a waterway as a means of penetrating a densely populated area. At that time published comments were very much associated with the operation of Autogiros, but they were equally valid for the helicopter. It seemed to him that if a pilot had to choose the lesser of two evils, an emergency landing on water was preferable to one on a roof. The river offered one particular advantage, that Mr. Colbeck had mentioned, in that it helped to alleviate the effects of noise. More important still, it provided unobstructed approach and take-off paths. It was for these reasons he believed that the river held such tremendous advantages. If one could imagine a 1,000 ft. square operating area at bridge level over the Thames, it meant that a helicopter about to take-off or land was at least half that distance removed from nearby offices and residences and from all those to whom noise could create a nuisance.

While distant approach by a waterway was not essential —he made that assumption for the simple reason that with multi-engined transport helicopters the risk of a forced landing was removed—it might well be found necessary within the central area to confine the flight of all helicopters at some stage or another to above the waterway.

The surface texture lighting of the platform had a softly diffused glow effect rather akin to daylight and this might be due to the fact that the concrete surface was slightly roughened and untreated as distinct from the shore area, which was asphalt.

In 1949-1950, when the B.E.A. Helicopter Unit was getting ready to operate the world's first scheduled night mail service by helicopter, between Peterborough and Norwich, it was found during early experiments that on a wet night there was a good deal of reflected light from a smooth concrete landing path. Roughening the surface dissipated reflected light and achieved the required improvement.

He thought Mr. Colbeck's assumption that the present number of landings might be trebled without increasing direct operating costs, was correct, although appreciably more traffic would be necessary to break even. That aspect was also influenced by size, because it was as easy to handle a big helicopter—looking at it from the point of view of its revenue-producing characteristics—as a small one. The bigger the helicopter, the better they liked it at the heliport—so long as it came in fairly frequently.

From the economic point of view, the revenue would increase as soon as multi-engined helicopters were operating. Perhaps he should add that the heliport staff would also increase, because then one envisaged 24-hour operation, whereas at present the activity at the heliport was more or less restricted to daylight hours.

R. B. Rofe (International Aeradio Ltd.): He knew nothing at all about helicopters, but he wondered if there were anything to be gained by going more for amphibious helicopters and not worrying about platforms but landing direct on the River Thames, or would that make the helicopter ungainly or more uneconomic in its operation?

The Chairman had mentioned navigational aids, which was rather in his line of business as he was an air traffic control officer. If Wing Cdr. Brie were restricted to the use of the Thames as an approach to the heliport, he wondered what sort of navigational aid he would use to give him the necessary accuracy. There was a navigational aid which would do it at the moment, but he would like to hear Wing Cdr. Brie's views on that subject.

Wing Cdr. Brie: The particular problem that arose with the Thames and with any tidal river, was that one could not at all times get amphibious helicopters close to the shore. They surmounted that problem by projecting the alighting area out into and over the waterway where they had clear approaches and convenient access to the passenger handling facilities. Experimental multi-turbine-engined amphibious helicopters had already been flown to and from the landing platform.

If helicopters were forced to use a river, the pilot would need some assistance in getting in under instrument flight conditions. Navigational aids were, after all, used to bring aircraft in at airports under extremely bad visibility and he did not foresee any difficulties in applying those same techniques to heliport operation.

Looking to the future, he thought that it would be much easier to control the approach and landing of a helicopter than was possible with an aeroplane, because of its very slow speed of approach. By what means that would be done he could not say.

G. W. Rooke (Lewis and Duvivier, Consulting Engineers): The construction of the heliport itself did not present any serious civil engineering problems. Nor would a heliport of greatly increased size present any serious difficulties on a site like that at Battersea.

The greatest difficulty which they encountered in its construction was to get it completed in the short time available. However, the landing platform was completed to schedule. The shore installation had been completed in reasonable time under difficult circumstances, but its arrangement had been dependent on Westland's requirements, which, as in the case of any "first effort," were difficult to decide, and Westland had to comply with a host of regulations imposed by all the various controlling authorities. He felt that, all things considered, everyone was extremely co-operative and the heliport had been brought into operation in a very creditable time.

It had certainly been a great pleasure to work on the project. It had been a happy job, and he hoped that some time later on he would perhaps have the pleasure of assisting in bringing a further heliport or heliports into being. He expressed his firm's thanks to Westland, with whom it had been a pleasure to work.

J. S. McHutchen (Manager, Westland Heliport): Westlands had asked International Aeradio Ltd. if they would provide operational management of the heliport and the necessary Air Traffic Control service. Nobody really knew what the air traffic control facilities required were, particularly for a heliport in the middle of the London control zone.

All the helicopters using the Battersea heliport had been single-engined except two prototypes. Therefore, they had to follow the River Thames which simplified the air traffic control problem. It was necessary only to provide procedural control of the aircraft along the river from Castlenau Reservoir to the west to Greenwich in the east. To keep them clear of fixed-wing traffic using London Airport they were also restricted as to altitude. Normally they could not clear helicopters above 1,000 ft. The

minimum separation for aircraft vertically was 1,000 ft. in I.M.C. Therefore, one could have only one aircraft at a time on the route (unless geographical separation could be provided). It might be possible and acceptable to have helicopters with 500 ft. separation vertically, but one had to be careful about altimeter errors if separation were reduced to 500 ft. vertically. They had no radio aids at the heliport apart from V.H.F. R./T. communication, and with that they could effect only procedural separation, which was by time, or geographically, at various points.

The type of radio aid that could possibly be used for Air Traffic Control was, of course, radar, but, there again, the siting of the aerials would be difficult. Fulham power station, with 300 ft. high chimneys, was almost directly opposite the heliport. With radar aerials put there, it should be possible to give good coverage. That coverage would have to be down to 500 ft. without any blind sectors. They found that with V.H.F. they had got good coverage with aerials sited on a 40 ft. mast on the heliport. In fact, it was quite normal to pick up a helicopter passing them an E.T.A. direct up to 30 miles away at a height of 1,000 ft. except in certain sectors.

During the shuttle service at the time of the Farnborough Air Show they had by far their maximum number of movements, apart from a little fun and games during the *Daily Mail* air race. The rate of movements reached the rather fantastic figure of one every four minutes for one period of 40 minutes. It was not a matter of one machine going up and down. Six different helicopters were involved on that occasion.

He did not suggest that they could handle that number of helicopter movements regularly, but it would be possible to handle considerably more than they had at present without any increase in staff. They could probably handle between five and six times as many machines comfortably without any increase in staff or cost.

It was possible to have a helicopter land, stop its rotors, be towed off, refuelled, turned round and take off again very quickly; it had been done with an S.55 in seven minutes.

The heliport was T-shaped, with an access ramp. Westland had good reasons for designing it like that, but there was a snag in that helicopters were restricted in access to and from the platform. He thought that the ideal would be more of a U-shape with access to the platform from two directions. The landing platform should be treated more like an aircraft runway so that it would be possible to have an aircraft at the holding point ready to take off while a landing aircraft was able to clear the landing area without conflicting with the departing helicopter.

He agreed with Wing Cdr. Brie that the river solved the noise problem to a great extent, but in a confined area of buildings as soon as a helicopter was clear of the actual landing platform and on to the ramp, the noise level was very high in respect of the surrounding buildings. Another point was that there was considerable downwash if machines were ground-taxied or air-taxied clear of the platform. Therefore it was almost essential to tow helicopters off and on to the platform.

The Fulham power station was a large obstruction but was not a major hazard to navigation because pilots were restricted to visual-contact conditions under special visual flight rules and had to maintain sight of the ground to be able to follow the river in all weather conditions. But the power station caused some trouble because of turbulence if the wind was from that direction. In the sector from west to north the turbulence could be considerable if the wind was more than 15 knots. That affected landings rather than take-offs. Again, with the wind direction from, say, east-north-east to south and coming from the landward side, a landing was no problem, but a take-off could be difficult.

Captain Gordon, the pilot who had done most of the flying at the heliport, was better qualified to talk about that than he was.

There was one interesting point, although he did not want to give additional statistics. The Army had used the heliport for the transport of its V.I.P.s more than both the Royal Navy and the Royal Air Force together.

Sqn. Leader A. W. Day (Aerodrome Owners Association): His interest in the subject as a whole went far outside London, and he welcomed the opportunity of saying that the construction, existence and operation of the London Heliport had had very beneficial effects throughout the whole of the country in whipping up the interest of Local Authorities in many cities and towns in the future of helicopter passenger travel, and in selecting and reserving suitable sites at which helicopters could land.

Another aspect of the activities of Westland Aircraft Ltd. was that they were exceptionally modest about what they had done. All along Westland Aircraft had said that it was a purely experimental project, purely a temporary measure, but he felt that their effort would go down in helicopter history as a great venture.

Those concerned with aerodromes were much interested in helicopter stations, heliports, or whatever the official name for them might be. There was a time when the Ministry had not made up its mind what it was going to call them, and he did not know that it had done so yet, but the first helicopter station in London had been called a heliport, and he hoped that that name would now catch on and be applicable to all future helicopter landing sites.

He spent a considerable time going around the country visiting Local Authorities interested in establishing helicopter stations for their respective areas, and took with him details and pictures of the London Heliport, which had created great interest.

Municipalities which might select suitable sites for helicopter landings were not being encouraged at this stage to construct heliports in any sense along the lines of the London Heliport. All they were being advised to do at the moment was to choose a suitable piece of land in the vicinity, preferably Corporation land, so that no cost would be involved in acquiring it, so that the London Heliport would know that there was a suitable spot to which it could send an aircraft.

The question of water access had been discussed. He felt that they had to remember, looking at the whole subject from a wide angle, that many of the cities and towns that must before long have heliports had not the advantage of a river. But they might have the advantage of comparatively open country in one or two directions into the town. London was fortunate, but many heliports of the future would have to be located in places where there would not be any river access.

Could Wing Cdr. Brie tell them anything about the experience at London Heliport from the meteorological point of view? For instance, on how many occasions had it been unusable on that count?

He gathered that aircraft had taken off from the London Heliport to more than 100 different destinations in the country. One would be interested to know—although the answer to the question might not be readily forthcoming—where they had landed, what kind of places they had gone to, whether much exploration had been necessary in order

to decide whether a man who wanted to go from A to B could land at B, and also, looking a little farther ahead—as he knew Wing Cdr. Brie was always doing—if he personally had the choice of a site for a future permanent London Heliport where would he locate it—elsewhere on the river, on the bank or, as had been mentioned on two or three occasions, over one of the existing railway termini? The last might be more practicable now that the diesel was coming in. Otherwise he could not imagine a more unsuitable place for trying to land a helicopter than on top of a railway station with holes in the roof with smoke pouring out in large volumes.

One of the speakers had said that he did not regard a T as an ideal shape for a heliport, but there was not much option for the existing London Heliport. He had always suggested to people in various parts of the country even if they were going to use a grass field to begin with, that from the point of view of landing points they should have a large X, which would provide four landing points, one at each of the extremes of the diagonals.

Wing Cdr. Brie: The question of the location in London that one would select as a site for a permanent heliport raised a problem which was at present being tackled by a well-informed Committee under the auspices of the Ministry of Aviation; its problem, he suspected, and as all who knew anything about the subject would appreciate, was that it was difficult to find a suitable area unless one were to make use of some site which was already being used for some other purpose. One thought in terms of parks. Why should not the middle of Hyde Park accommodate a heliport? It was a site which offered many advantages.

He thought that railway termini had a great potential to offer, not necessarily the roofs of stations, but the adjacent main lines or marshalling yards. Why not enclose existing railway lines, and thus have a fairly low-level heliport? One did not want to go too high. If one thought in terms of putting a heliport on an existing station roof one ran the risk of bogging down helicopter movements when there was low cloud and so on, whereas at near surface level that would not happen. In any case, other considerations attached to the use of a roof over an existing facility, including refuelling. He felt that posed a major problem.

He still felt that the river could provide the ideal overall solution for London. He could well visualise a bridge structure, but it would not conform to conventional practise. He was thinking of a reinforced concrete structure at bridge level measuring 1,000 ft. square with suitable vehicular access to both shores. That, indeed, would provide an adequate Central London Heliport at minimum cost for it could accept the biggest helicopters and a high rate of movement for many years ahead. One must have sufficient surface and unobstructed air space, and by using that freely available over the river in the way he had suggested, one would be providing not only a means for helicopters to operate without hindrance, even to the extent of simultaneous approaches and take-offs, but adequate room for parking and all other essential facilities. It would even be possible to get the vehicles that carried passengers to and from the heliport off the streets because there would be enough parking space on the perimeters.

Such a structure over the river could well provide an acceptable solution. A suitable location might be between Waterloo and Blackfriars Bridges, which was getting a reasonable distance away from the Houses of Parliament.

Among those present was Mr. Alistair Gordon, who had more experience of pilotage out of the London Heliport than any other pilot, and perhaps he would answer Sqn. Ldr. Day's query about what happened when passengers came along and chartered trips, the direction in which they took him and what steps he had to take to ensure that when he reached the other end he could land.

A. C. Gordon (Bristow Helicopters Ltd.): The question of direction was rather difficult to answer. The operation of a charter service at the present stage was quite expensive per passenger. Obviously, the charterer was connected with a company. Therefore, the charters so far had inevitably been from London to some form of industrial estate or something of that nature, and inevitably those were centred round the industrial towns of the Midlands etc. Where the site was congested from the point of view of the limitations imposed upon single-engined helicopters, they had occasionally had to use the nearest airfield, which was uneconomic, for although one started off in the centre of London one ended up at the other end no better off than if one had taken a fixed-wing aircraft.

As to the selection of a site at the other end, the charterer was usually in the best position to tell them where it was possible for the helicopter to land. It was usually on his property or on a piece of land in the vicinity which he knew. They then had to ascertain the dimensions of the land and the suitability of the approaches, and so on. To do that they had to have scale maps sent beforehand and approved from the operational point of view and, if there were any doubts, they must also be checked by the Ministry. That was quite a point when it was virtually a taxi service that one was operating. At the present stage it was practically impossible for someone to telephone and say " I should like to go to such-and-such a place " because there were no known heliports available and it was difficult to get necessary information to decide on a site and obtain permission for landing.

With regard to the question of the weather, during January they had in all 18 charters booked and they cancelled 12 because of the weather on the route. They had found that where a pilot knew the route intimately he could cope with 800 yds. visibility at 500 ft., but if the visibility dropped much below 800 yds. he was forced to go below 500 ft., which was infringing the minimum height rule. Therefore, without twin engines one could not really improve on that except in the open country. An aid would be of no great value because one had to come lower with it to retain " contact," and one was limited to 500 ft. height.

H. Sims (Director, H. J. Sims and Partners, *Associate*): What was the ratio between the money that the Government had spent at London Airport recently and what had been spent on the London Heliport, and also the ratio between what the Government had done to develop helicopters and what private enterprise had done? He felt that the way the Government was going on was disappointing.

It seemed to him that the Government were tackling the problem of the provision of heliports in the same way as they were tackling the problem of the roads, in that they did nothing until it was too late. Now was the time for the Government to look ahead in respect of the provision of heliports, instead of waiting for he did not know what.

Wing Cdr. Brie: Frankly, he could give only a generalised answer. He took it that Mr. Sims was referring to the economics of heliport operation.

Mr. Sims: He was referring to the amount of money that had been spent by the Government on London Air-

port to improve it from the point of view of the passengers. But the Government were not doing anything about the provision of heliports, which were essential to the country. In 20 years time the Government would be tackling the matter in much the same way as they were doing the M.1 now.

Wing Cdr. Brie: He was afraid that he could not give Mr. Sims an adequate reply because he did not know the answer. Westland had not asked for any financial assistance, but whatever help they had asked for from the Ministries, not only the Ministry of Aviation, but other Ministries as well, had been freely given. He could speak only from the experience of his company. He was unable to comment about the position at the London Airport because that had nothing directly to do with the heliport.

Mr. Sims: Could he visualise the Government treating the provision of heliports in the same way as they had treated the provision of motorways? In view of the amount of traffic on the roads nowadays, the Government were now looking into the problem of the roads, whereas they should have begun to look into the problem when the horses and carts started to disappear from the roads.

Wing Cdr. Brie: The difficulty experienced in regard to the provision of heliports was really due to the fact that the right types of helicopters were only just about to become available. One could not have single-engined helicopters buzzing around indiscriminately. One had to ensure reasonable safety conditions to third parties as well as to the user. They could now see the near future availability of multi-engined helicopters. They would be operating in America next year and this was bound to stimulate the provision of heliports elsewhere.

A Ministry of Aviation committee was now deciding where there should be a Central London Airport. It had a problem on its hands, but he had no doubt that it would produce an answer. What was happening with heliports was typical of what happened with any new form of development. It took a long time to get it accepted, but the helicopter had now reached the stage of acceptability. When the public could see real usefulness in helicopter travel, heliports would spring up all over the country.

Commander W. G. Boaks: He had a large number of planning applications before the Ministry of Housing and Local Government for stations on the river—16 riverside air stations which would be floating platforms. That method of using the river was placed before the Ministry of Civil Aviation in 1954.

In view of his support for the use of the river, could Wing Cdr. Brie explain why the Ministry had kept that particular proposal in its files for six years and had not developed it, and why the Westland Aircraft Company had ignored all the proposals which he had put before it and the Ministry of Transport and Civil Aviation? He could not see why the Ministry had not given the Ministry of Housing and Local Government its fullest support for a proposal which had been placed before it time and time again. Proposals were put before the Ministry in May two years previously, as a result of which Westland had its proposal approved, but Rotorports had its discarded.

The proposal which he had put forward was to have floating platforms adjacent to public right-of-way stairs so that any aircraft entering London, or in difficulty, could alight at once at those sites in the densely crowded and built-up area.

Despite the persistence with which he had plugged his proposals, he had had no help from the Westland Aircraft Company, Faireys or the Bristol Aircraft Company in respect of a problem which concerned all three companies. Nor had he had any help from the operators.

He wondered if Wing Cdr. Brie could explain his Company's views in respect of its reluctance to be associated with his proposal and the reluctance of the Ministry of Aviation to be associated with it. It would cost about £1 million as opposed to the large sum which was being spent on London Airport.

Wing Cdr. Brie: He would confine his comments purely to the remarks made by Cmdr. Boaks in relation to the Westland Aircraft Company. He could not speak for anybody else. When Cmdr. Boaks said that Westland had refused to assist, he was stretching his imagination. Westland's original idea was to make use of a floating platform, but it was realised that in a tidal waterway one could encounter difficulties in getting passengers to and from the shore. They had reconsidered its original proposal, as it had every right to do, and had decided to embark on the project which had now been completed, and the result was something which was practical and in day-to-day use.

He could assure Cmdr. Boaks that Westland had no axe to grind with anybody. It wished to give all the help it could to those able to assist the movement. Before the Westland Heliport became saturated with traffic it was essential for additional facilities to be provided.

But why should the Westland Company set out to build heliports all over the place? It was primarily interested in constructing helicopters, not heliports, and he thought that Cmdr. Boaks was not fair when he implied that Westland had somehow frustrated his hopes.

I. D. Roxburgh (Ferranti, Ltd., *Associate*): There were two promising developments in relation to the helicopter instrument approach requirements. Firstly, a micro-wave I.L.S., which would permit approaches of up to 20° glide slope to be performed. Development of micro-wave I.L.S. was being carried out by B.L.E.U., R.A.E., Bedford. Secondly, an extension of the Decca Navigator System, provided that the Decca stations could be suitably positioned, could enable instrument approaches to be made down to a sensible break-off height.

The development of approach aids, however, was just one aspect of the many problems to be met in achieving all-weather operation of helicopters.

G. I. W. Dunford (International Aeradio Ltd.): He wished to enlarge a little on helicopter operations. In respect of movements from one heliport to another, he wondered whether Wing Cdr. Brie could tell them something about the economical cruising levels of helicopters and about any plans to provide helicopter lanes between established heliports.

Wing Cdr. Brie: At present established heliports were much at a discount.

Mr. Dunford: He had in mind the situation in the future.

Wing Cdr. Brie: He thought that the pattern had been established. The activities over the years of B.E.A., and now Bristow and other operators from the Westland Heliport had established a certain standard and, as had been mentioned by Mr. Colbeck, no particular problem had arisen in handling helicopter traffic in the London zone.

Mr. Dunford: That was probably because there was such a low rate of traffic, but when there was a higher

rate helicopters would probably have to cruise at a higher level.

Wing Cdr. Brie: Mr. McHutchen had stated that as the frequency went up there would have to be fresh rules and regulations. That was understandable. At present with 1,000 ft. separation one could not separate helicopters in that sense. He had no doubt that such problems were being considered and would continue to be considered, but he thought that only time could resolve how helicopters would be integrated in that wider sense.

One could envisage certain areas becoming quite congested with helicopters alone in the years ahead, and there was no doubt that in such areas something like the Decca system would be indispensable, and perhaps one could look to lateral and vertical separation of 500 ft. without anxiety.

Mr. Dunford: Could Wing Cdr. Brie tell him the operational cruising level of a helicopter, including that for the multi-engined helicopter, at the present time; later on they would obviously want to go up higher to be economical.

Wing Cdr. Brie: That would depend on the type of helicopter produced and the stage length. Helicopters flying between London and Paris might want to go up to 8,000-10,000 ft., but for short-distance activities, possibly 25 or 50 miles, an operator would not want to waste time gaining altitude but would want to get to his destination as soon as he could. At altitudes greater than 10,000 ft. they would be penetrating an environment where it was not unreasonable for conventional aircraft to be operating.

Mr. Dunford: What was an economical stage length where a piston-engined or fixed-wing aircraft scored over a helicopter? Between London and Paris, for instance, could a helicopter do the journey in a faster time from an airport situated nearer the centre of the town than a fixed-wing aircraft could?

Wing Cdr. Brie: A helicopter capable of cruising at 150 m.p.h., going from point to point, from the centre of London to the centre of Paris, could do the journey faster than any other aircraft when the passengers had to waste time going from the centre of the city to an airport on the outskirts, for that was where most of the time was wasted. Probably 200 miles was about the limiting route stage length with a helicopter.

R. B. Rofe: How long would it be before it was as cheap to go from London to Paris by helicopter as it was by fixed-wing aircraft, bearing in mind the attendant inconveniences involved in getting to airports? The problem seemed to be that helicopter travel was still rather a luxury and could be afforded only by the large business concerns which could set off the expenditure against the time saved by their employees. In other words, when would helicopter travel be available to ordinary folk who had to pay for their own tickets?

Wing Cdr. Brie: He understood that B.E.A. proposed to start a twin-turbine passenger service between Penzance and the Scilly Isles in two years time, and the rates charged would be strictly comparable with what it already charged on its Rapide service. He could not go beyond that. Obviously, helicopters had to get bigger in order to operate at a reasonably economic level. It had been suggested that for the Fairey Rotodyne, a 60-seater, the cost per passenger per mile would come down to 4½d. That was slightly on the high side, but was without any subsidy. When one considered that most modern airlines were subsidised in one form or another, even if it were only through air mail, there was no reason why passenger travel rates with helicopters, when the right types of helicopters were produced, should not be at least comparable with those charged for conventional aircraft.

Mr. Rofe: His estimate was roughly two years?

Wing Cdr. Brie: That was so. It should not be forgotten that one would have to go to Penzance to take advantage of that luxury. He had given Mr. Rofe the answer to his question as he saw it. In two years time, if he were so minded, Mr. Rofe would be able to fly between Penzance and the Scilly Isles at a cost comparable with what one would pay in a fixed-wing aircraft.

A Speaker: One could do it today if one crossed the Channel.

The Chairman (Mr. Hill): Today the Viscount was scheduled to fly from London Airport to Le Bourget in around 65 minutes and the DC-8 could scarcely improve upon that, as evidenced by recent trials. The passenger, however, was interested only in the centre-to-centre elapsed time and this meant by the use of road vehicles and a scheduled air liner, an overall journey absorbing anything from 4 hours 15 minutes to 4 hours 30 minutes. In a developed helicopter it should easily be possible to travel from City centre to City centre in two hours. Indeed, even today, it was possible to take a train from Victoria, cross the channel by air, alight at Le Bourget and proceed to the air terminal in Paris in less time than the four or four-and-a-half hours mentioned as the scheduled airline time.

He had thought a good deal about the amphibious helicopter and its attractions to the passenger and agreed that such a machine for over-water journeys certainly offered a much improved sense of comfort and security. He saw, however, a passenger transfer problem for those concerned with the maintenance of a good passenger flow.

To act as Chairman at this lecture had given him great satisfaction for he had in the course of the years watched Wing Cdr. Brie's progress and energetic activity as the leading advocate of the helicopter, with much pleasure. He wished to again congratulate Wing Cdr. Brie on the factual and practical way in which he had described this very worthwhile project, namely, the Westland Heliport, and to congratulate the Westland organisation in bringing the project to its present successful stage.

Some British Research on the Basic Aerodynamics of Powered Lift Systems*

by

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SUMMARY: The paper mainly discusses recent R.A.E. and N.P.L. research on the aerodynamics of Direct jet lift (turbo-jet and turbo-fan), Propeller lift (tilt-wing and deflected slipstream), Jet flaps, and Boundary layer control (blowing and suction). Some of the work at Firms and Universities is also mentioned where the information has been made available for general circulation. Attention is drawn to the present state of knowledge in relation to V.T.O.L. and S.T.O.L. aircraft applications and to some major aerodynamic problems which need further study.

1. Introduction

In this appraisal of some recent British research on the aerodynamics of methods for providing adequate lift at low and zero forward speeds, the work will be classified for convenience under four broad headings as follows. The first two items are relevant to both V.T.O.L. and S.T.O.L. application, but the last two are primarily applicable for S.T.O.L. operation or for improving the forward flight performance of V.T.O.L. aircraft (*e.g.* through transition).

(*a*) *Direct jet lift* (*Section 2*) with "round" jets directed downwards, in an attempt to provide lift augmentation roughly equal to the vertical component of the rate of ejection of momentum. The mainstream flow over adjacent surfaces may be markedly affected by the presence of the jet efflux or intake suction, while at zero mainstream speed the flow pattern induced by the jet can be significant near the ground. Such interference effects can vary appreciably with the ratio of jet exit area to wing area (or wing loading to disc loading) which for practical V.T.O.L. aircraft tends to increase with the change from high velocity jets (pure turbo-jet) to low velocity jets (fan systems, integral or remotely driven). The intake flows associated with fan-lift systems also need special consideration, both as regards their effects on the external surface flows and the internal flow requirements at the fan disc.

(*b*) *Propeller lift* (*Section 3*) with the thrust of the propulsive propellers turned to give a lifting component, either by tilting the propeller-wing combination towards the vertical, or by deflecting the propeller slipstream using an elaborate flap system. With the tilt-wing a simple slotted flap is often incorporated to assist transition between hovering and forward flight, while with the deflected slipstream arrangement a large wing-ground angle is usually needed to deflect the thrust vertically without undue loss of efficiency.

(*c*) *Jet flaps* (*Section 4*) with a large proportion of the efflux of the installed gas turbines ejected as a plane sheet over the wing trailing edge at an angle to the mainstream. This represents an attempt to integrate (at least partly) the propulsive and lifting systems, the vertical component of the jet momentum being magnified several times by the "pressure lift" generated on the wing surface. The incorporation of a small trailing edge flap, whose angle can be simply varied, is intended primarily as a practical method of altering the jet angle without varying the inclination of the blowing slot.

(*d*) *Boundary layer control* (*Section 5*), by using a small proportion of the installed engine power to induce blowing or suction at the wing surface, for the prevention of flow separation which tends to occur on the upper surface of the wing nose and the trailing edge flap knee. This represents an attempt to attain the ideal lifting efficiency of the system corresponding to potential (inviscid) flow.

Most of the research work discussed here has been carried out at the R.A.E. and the N.P.L. Some of the work at Firms and Universities is also mentioned, where the information has been made available to the author and released for general circulation. Attention is drawn to the present state of aerodynamic knowledge in relation to possible V.T.O.L. and S.T.O.L. aircraft and to some major problems which need further study. Unless otherwise stated, the experimental measurements (and theories) discussed here refer to *stationary* models in a low speed mainstream. Clearly, the effects of *oscillatory* motions on the aerodynamic forces also need investigation, to justify the use of quasi-steady treatments for the evaluation of the dynamic derivatives.

Three other lift augmentation schemes, though not discussed here, warrant special mention. Firstly, spanwise blowing can increase the effective aspect ratio by controlling the tip or edge vortices. Some wind tunnel experiments have already been completed with the air discharged spanwise (horizontally or downwards) from the wing tips[62, 63] or edges[64] of the plan form, or chordwise and downwards from tubes extended spanwise out of the wing tips[65, 66]. However, much further research is necessary to make full-scale application attractive and practicable for S.T.O.L. Secondly, air-cushion support of vehicles in close proximity to the ground can be provided very economically as demonstrated on the Hovercraft[67], using peripheral (and

*The second lecture given before the Rotorcraft Section of the Society—on 4th March 1960.

other) types of jets. The importance of this concept in relation to both V.T.O.L. and S.T.O.L. aircraft should not be overlooked*. Finally, lifting rotors already in everyday use for helicopters and the like could probably have their aerodynamic efficiency improved, particularly at forward speeds; the application of boundary layer control and jet flaps is worth further consideration in this context.

NOTATION

A	wing aspect ratio
b	wing span
c	wing chord
c_f	flap chord
C_L	lift coefficient $= L/q_0S$
C_D	drag coefficient $= D/q_0S$
C_X	thrust coefficient $= X/q_0S$
C_m	moment coefficient $= m/q_0Sc$
C_μ, C_μ'	blowing momentum coefficients $= MV_J/q_0S, \quad MV_J/q_0S'$
C_{Jt}	jet-reaction coefficient at tail $= J/q_0S$
C_Q	flow coefficient $= M/\rho_0V_0S$
d	diameter of jet exit or propeller diameter
D	diameter of circular wing {or $2\sqrt{(S/\pi)}$}
G	downward suction on wing arising from ground effect
h_t	height of tailplane above fuselage centre line
H	height of jet exit above ground
l_v	coefficient of rolling moment due to sideslip
M	mass flow rate, measured
n_r	coefficient of damping in yaw due to yaw
n_v	coefficient of yawing moment due to sideslip
q_0	mainstream dynamic head
q''	dynamic head of slipstream (with mainstream)
R_c	chord Reynolds number
S	gross wing area
S'	reference wing area corresponding to spanwise extent of blowing or suction
S_J	area of jet exit
T	installed thrust
T_c, T_c''	propeller thrust coefficients $= T/2q_0D^2, \quad 4T/q''\pi D^2$
V_0	mainstream velocity
V_J	jet velocity
V_S	suction inflow velocity
α	wing incidence
$\Delta\alpha_t$	change of tailplane incidence
ε	angle of downwash relative to mainstream
θ	jet-angle deflection
η	flap angle
ρ_0	mainstream density

2. Direct Jet Lift

2.1. GENERAL COMMENTS

As background to the experimental model programmes, the scope of relevant flight work at the R.A.E. and the respective firms needs to be mentioned. Jet deflection flight tests on a Westland modification of a Gloster Meteor[1] began in 1954, to provide much needed guidance on the novel control and handling problems arising from reduction of approach speed by such means, in particular the effect of the inter-connection of thrust and lift on flight path control. About the same time, operational experience on automatic control systems for V.T.O.L. aircraft was being obtained from hovering investigations on the Rolls-Royce "Flying Bedstead" supported by two lifting turbo-jets (Nene), without aerodynamic surfaces. The Short S.C.1 research aircraft was then built with four lifting turbo-jets (R.B.108) located centrally in its delta wing plan form and with an additional turbo-jet solely for propulsion. For stabilisation or control during hovering and low-speed flight, jet-reaction controls can be operated manually or through auto-stabiliser units developed from experience on the "Flying Bedstead." Vertical take-off and landing operations have already been successfully completed and transition flights are in progress. This research aircraft should provide essential information on the stability and control of V.T.O.L. and S.T.O.L. jet lift systems in general, as well as on the degree of auto-stabilisation required with the particular layout under test.

During the past five years, there have been several project studies on possible military and civil aircraft incorporating lifting jets, using either turbo-jets directly or fan systems both integral and remotely driven. Exploratory tests of V.T.O.L. models were first made by Shorts[2] and Rolls-Royce on delta wing plan forms with central jet exits and intakes, in connection with S.C.1 research aircraft. Similar model tests in support of project studies on lifting-fan layouts were started at Boulton Paul. More recent aerodynamic research at R.A.E. and N.P.L. has been planned primarily to clarify the basic aerodynamics of turbo-jet and turbo-fan lift schemes, to support the design and development of the foregoing aircraft configurations and to provide data for further project work. Past model tests have mainly concentrated on wing installations, but new models are currently being designed to study the fuselage and nacelle type of installations.

2.2. STATIC MODEL TESTS

With jets emerging from the centre of a wing, as distinct from peripheral (annular) jets, entrainment of the air between the lower surface and the ground generates a suction on the lower surface (*see* Fig. 1(*a*)); this can lead to both a reduction in vertical thrust and undesirable moments. Extensive model tests were carried out at the R.A.E.[3], first on simple circular and triangular plan forms with a choked jet through a circular orifice at the centre of area, and then on a scale-model of the S.C.1 configuration. The ratio of the jet diameter $d\{=2\sqrt{(S_J/\pi)}\}$ to wing "diameter" $D\{=2\sqrt{(S/\pi)}\}$ was of the order 0·1, *i.e.* representative of lifting turbo-jet configurations. The ratio of the downward suction G (arising from ground effect) to the gross thrust T (in the absence of ground) was shown to be primarily a function of the ratio of the ground clearance H to the wing diameter D, as plotted in Fig. 1(*b*). The further parameter d/D and jet Reynolds number appeared to be only of secondary importance over the range of tests, increase in either tending to be

*The ratio of ground clearance to wing chord (or equivalent diameter) is likely to be greater for such aircraft than for the Hovercraft and the lift augmentation correspondingly less.

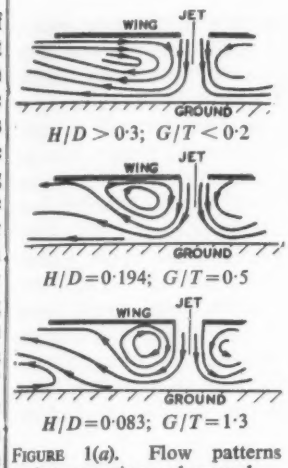


FIGURE 1(*a*). Flow patterns between wing and ground.

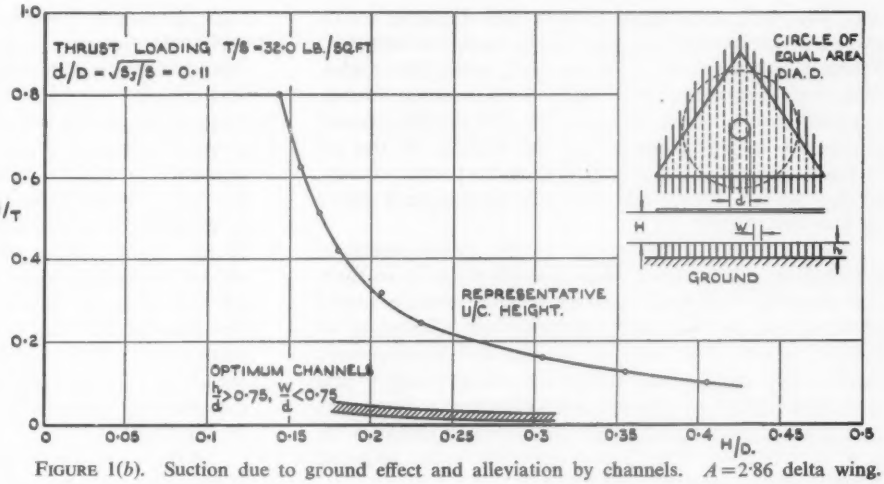
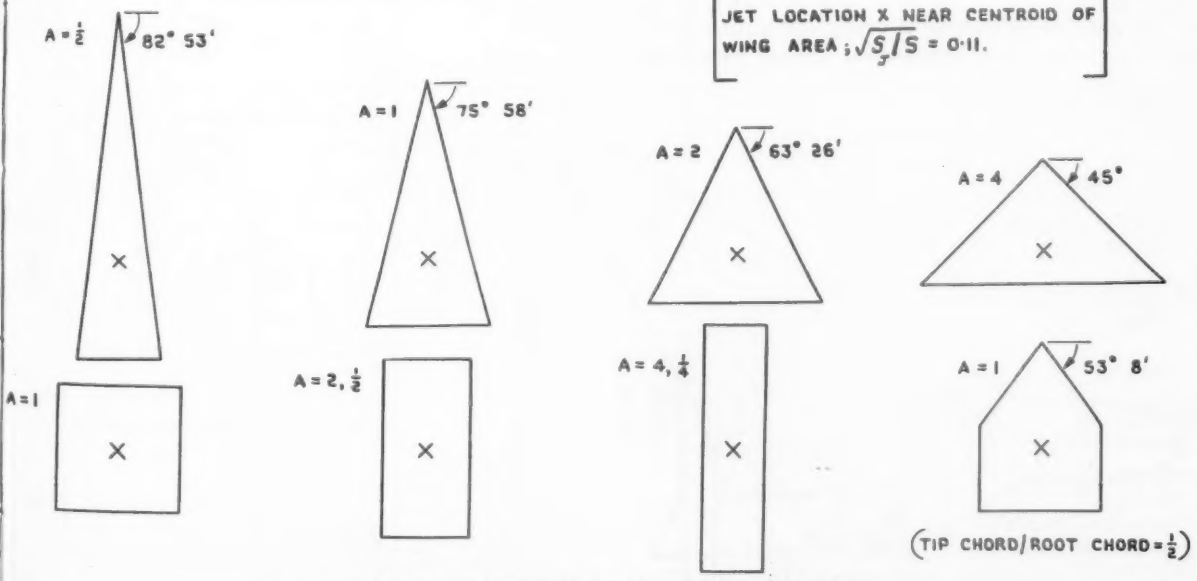


FIGURE 1(*b*). Suction due to ground effect and alleviation by channels. $A = 2{\cdot}86$ delta wing.

favourable toward reduced ground effects. The S.C.1 arrangement could lose some 20 per cent of its gross thrust T and experience strong nose-up pitching moments at a normal undercarriage height ($H/D \simeq 0{\cdot}3$). However, this loss could be reduced to about 2 per cent and the pitching moments made negligible by an array of parallel channels on the ground (Fig. 1(*b*)), to prevent radial spread of the jet efflux over the ground beneath the wing. This series of tests on adverse ground effects has recently extended to the wider range of plan forms shown in Fig. 2. Other simple studies have suggested some promising alternatives to channels and more extensive experiments are warranted.

Measurements on a lifting-fan wing have been completed at Boulton Paul[5, 6] and at N.P.L.[4] with much larger ratios of jet to wing area than in the R.A.E. pure jet experiments. The N.P.L. model consists of a single fan mounted centrally in a hexagonal wing whose size could be varied to give $\sqrt{(S_J/S)}$ ratios between 0·2 and 0·5. As expected, the wing acted quite efficiently as a shroud, the total lift (fan and wing) away from ground being some 60 per cent higher than that for the fan alone at the same power input, due to the reduced pressure over the wing upper surface associated with the inflow to the fan. At the lower area ratios, ground effect caused much the same reductions in lift as in the R.A.E. pure jet tests on circular and delta wings. However, at the higher ratios, the suction on the lower surface due to ground effect was counterbalanced by the increased pressure on the lower surface of the hub, arising from the curvature of the "annular jet". For example, at $H/D = 0{\cdot}2$, a loss of 10 per cent in lift for $\sqrt{(S_J/S)} = 0{\cdot}33$ became a gain of 10 per cent for



Also circular plan forms with $\sqrt{(S_J/S)}$ varied from 0·11 to 0·29.

FIGURE 2. Additional plan forms for static model tests of ground effect on direct jet lift.

$\sqrt{(S_J/S)}=0{\cdot}5$; with larger hub to fan diameter ratios even more favourable ground effects would be expected. From comparative tests on an early wing fan model, first with untwisted and then with twisted blades, Boulton Paul[5, 6] have deduced that the adverse ground effects are largely governed by the velocity of the air at the periphery of the jet rather than the mean velocity, so that the fan efflux might with advantage have a sleeve of low velocity air.

Fundamental investigations on the development of a turbulent jet in still air when it impinges on a surface, the so-called turbulent wall jet, could provide useful guidance on the practical behaviour and alleviation of ground effect. The problem of normal impingement onto a flat surface was examined theoretically[7] and experimentally[8] at Manchester University a few years ago, and some experimental fundamental research on wall jets and on jets issuing parallel to an adjacent surface is in progress at N.P.L.

The upward convection of hot gas on jet lift aircraft in the presence of the ground can lead to recirculation into the engine intakes. A few qualitative experiments have been made[9] to explore this convection phenomenon for the S.C.1 layout, using carbon dioxide for the jet and inverting the model with intake suction also represented. The results showed that, although uncovered channels tended to alleviate the amount of recirculation compared with the plain ground, the introduction of a gauze landing platform over the channels removed this favourable effect because the horizontal outflow was decelerated. Further model research on recirculation and its prevention is needed with centrally located jet exits (and intakes) and other configurations, using more representative hot jets if possible.

2.3. WIND TUNNEL EXPERIMENTS

Low speed wind tunnel experiments on jet deflection began at the R.A.E. in 1953 on partial models of the nacelle and nearby wing of the modified Meteor installation. Pressure and temperature surveys were made over the nacelle lower surface of a small model with a one inch diameter hot (and cold) jet, together with temperature measurements over a ground board. Force and nacelle pressure measurements were made on a larger scale model with a $4\frac{1}{2}$ in. diameter cold jet (fan-driven) both without and with ground. Simple blowing and suction models were used by Shorts[2] to represent the S.C.1 lifting turbo-jet layout and by Boulton Paul to simulate various lifting-fan wing projects. The effects of the lower surface jet efflux and the upper surface intake suction were determined separately. These tests showed that a significant interference could occur between the jet efflux and the mainstream flow over the wing surface, and indicated that the ratio of mainstream speed V_0 to jet speed V_J was the primary non-dimensional parameter for a specific geometrical arrangement.

More extensive research was next carried out at N.P.L., with a single-fan located at $0{\cdot}425c$ in a simple rectangular wing of aspect ratio 2 with $\sqrt{(S_J/S)}=0{\cdot}11$ (Fig. 3)[10, 12], and also near the apex of a swept wing with $\sqrt{(S_J/S)}=0{\cdot}22$ (Fig. 3)[11]. Both models were tested tail first as well, to vary the amount of wing surface aft and ahead of the fan. These experiments and most subsequent ones, included lift, drag and pitching moment measurements with the ratio V_0/V_J and wing incidence varied, as well as some pressure-plotting of the wing surfaces and traverses of the jet at fan exit. When the mainstream speed was increased from zero, at zero incidence, a loss of up to 20 per cent in lift occurred initially due to lower surface suction aft of the jet exit, though this was more than counter-balanced by an increase in lift as the mainstream speed

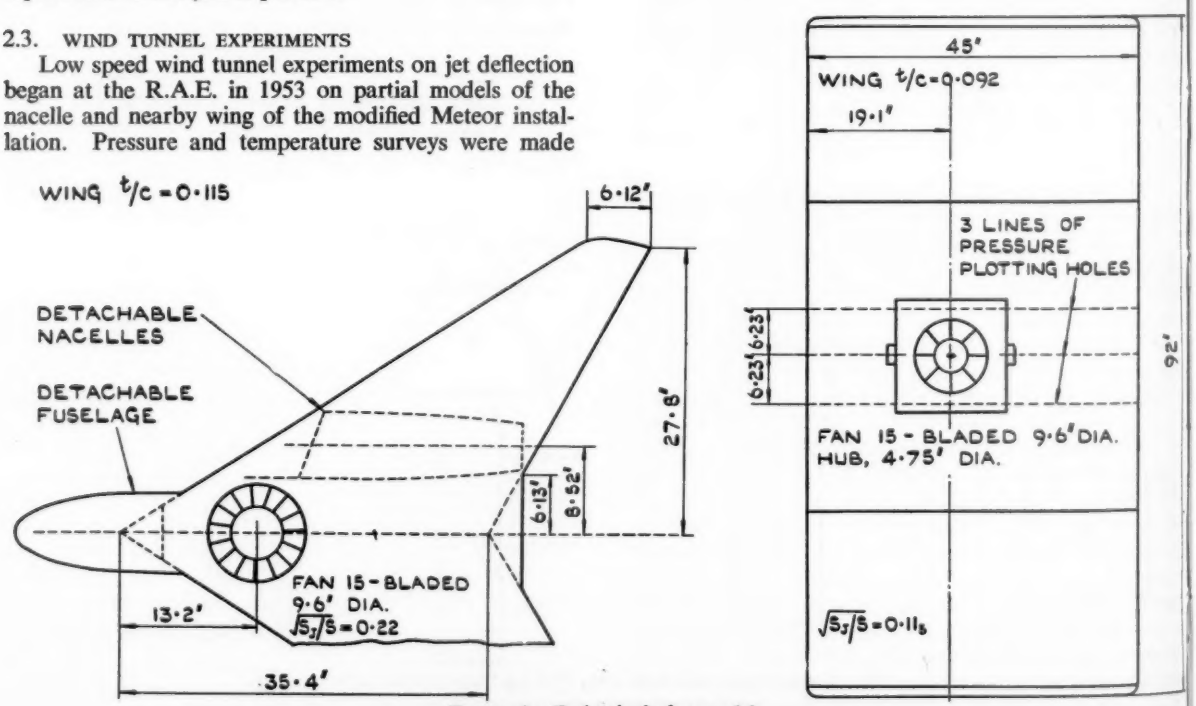


FIGURE 3. Early single-fan models.

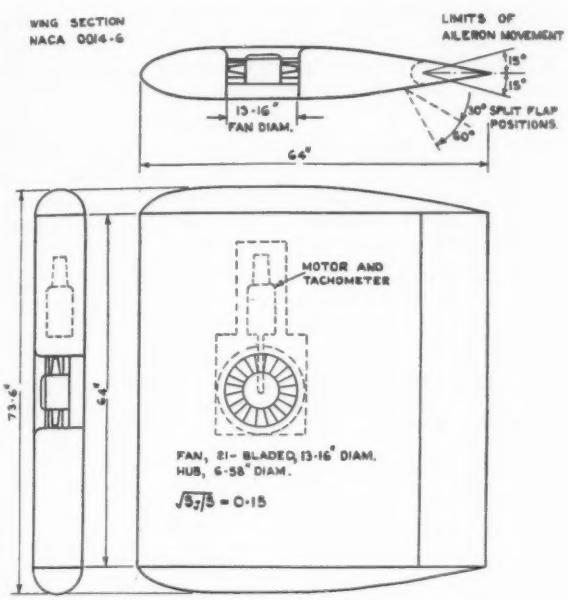


FIGURE 4. Single-fan model A.R.1 rectangular wing.

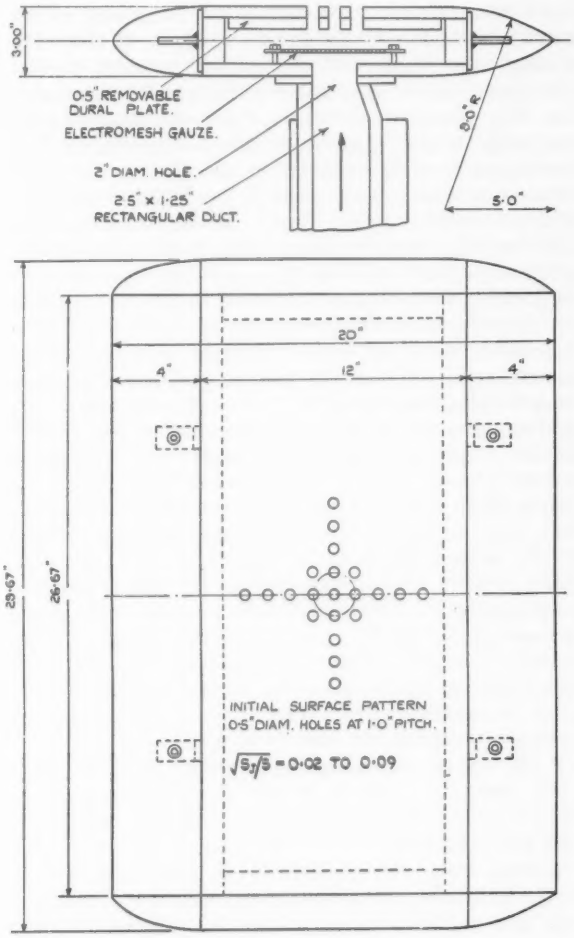
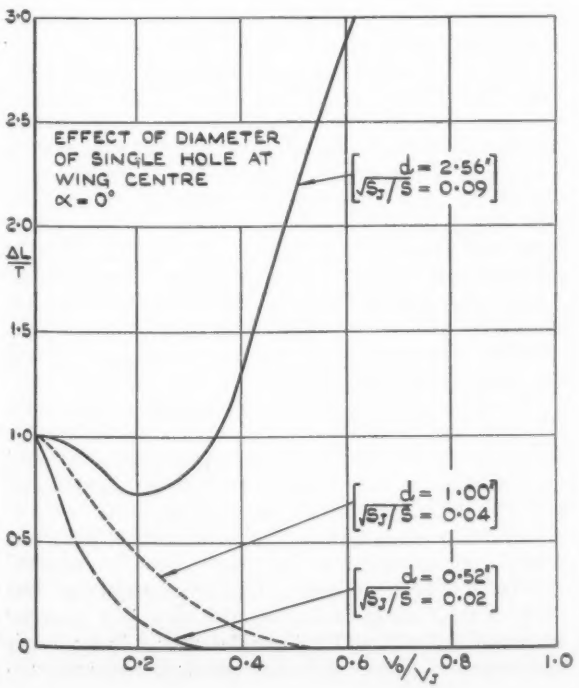
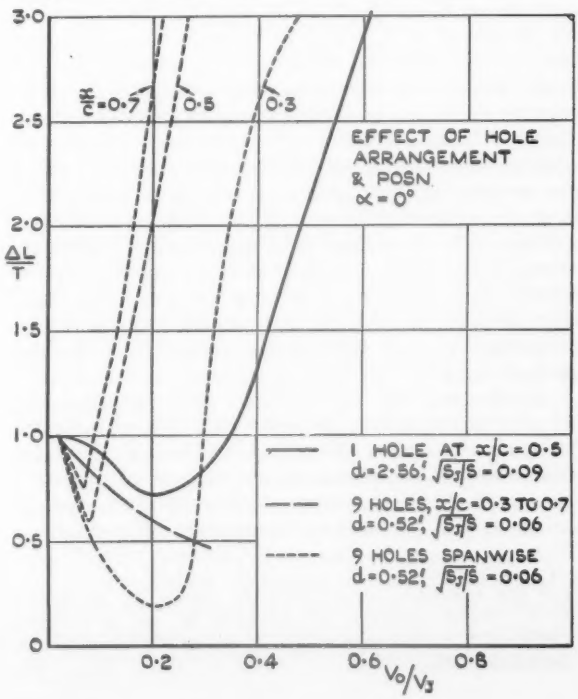


FIGURE 5(*a*) (*right*). Simple multi-jet model. Wing section—elliptic nose, parallel centre section and circular arc trailing edge.

FIGURE 5(*b*) (*both diagrams below*). Simple jet-blowing model.





was further increased. Simultaneously, the centre of lift moved forward from the fan to upstream of the wing leading edge, because of the reduced pressure on the rear lower and forward upper surface of the wing; also the drag increased above the value corresponding to the intake of mainstream momentum (sink drag). The investigations drew attention to the adverse effects of large wing areas downstream of the lifting-jet because of the reduced pressures there. It was found that the addition of dummy engine nacelles could considerably alleviate such adverse effects, so that the representation of nacelles, fins and fences as well as jet or fan layout can be important when testing a specific aircraft configuration. Further basic research on the external aerodynamics of multi-jet (pure-jet and fan) systems is mainly being carried out at the R.A.E., while fan inlet and exit flow problems are being studied at N.P.L. (*see* later). Exploratory tests have already been completed on the simple multi-jet rectangular-wing model shown in Fig. 5(*a*). The wing consisted essentially of a pressure box from which air was ejected through holes in the lower surface, the hole size, number and disposition being varied, with the mass flow carefully controlled and measured. More elaborate tests are now being completed on another rectangular-wing model (Fig. 6) with up to four fan units which can be used one or more at a time and set out in various arrays over the central part of the rectangular plan form; *e.g.* singly, in a spanwise or chordwise row, or in a cluster.

The test results from the multi-jet wing model[14] show that the initial fall off in lift, which occurs when V_0/V_J is increased from zero at constant incidence, becomes smaller in magnitude as the ratio of jet exit to wing area is increased. At very low ratios, $\sqrt{(S_J/S)} < 0{\cdot}04$, the lift increment due to a single jet can fall to zero (*see* Fig. 5(*b*)), but for ratios more appropriate to practical fan-lift wings $\{\sqrt{(S_J/S)} \lessapprox 0{\cdot}2\}$ the lift fall-off is not likely to be more than a few per cent. It is important therefore that subsequent wind tunnel models should employ values of $\sqrt{(S_J/S)}$ more appropriate to the practical application under study, say $S_J/S \lessapprox 0{\cdot}2$ and $0{\cdot}1$ for fan-lift and pure jet-lift aircraft respectively. The lifting effectiveness at forward speed can be improved by rearward movement of the jet exit, both as regards reduction of the initial fall-off and increase of the magnification at higher speeds. Furthermore, multiple jets can profitably be mounted close together in a spanwise row towards the rear of the wings (Fig. 5(*b*)), presumably because they act as a line source or jet-flap on the wing lower surface and thereby produce extra lift by super-circulation.*

As forward speed is increased, wing incidence can be used to supplement or replace the lift arising from the operation of the lifting jets. However, transition studies involve considerations not only of adequate lift but also the horizontal thrust needed from deflection of the lifting jets (or auxiliary propulsion units), together

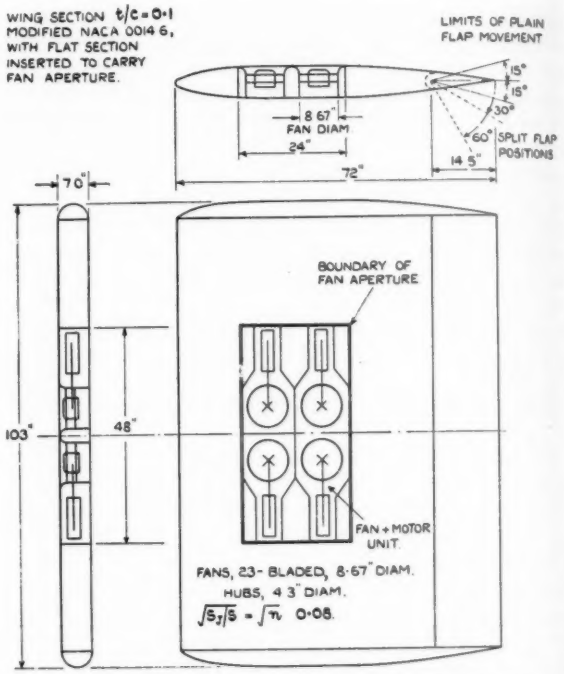


FIGURE 6. Multi-fan model. A.R. 1½ rectangular wing.

with the maintenance of stability and control, for variations in wing incidence and the power supplied for lift. The mutual interference between the air flow through the lifting engines (pure-jet and fan) and the mainstream flow over the adjacent wing (or body) can radically affect such analyses and can vary appreciably according to the layout used. Again, when low transition speeds are required, either from inlet "sink-drag" or other considerations, a good high lift performance is desirable without jet lift.

Six-component force measurements have already been started on a model, with blowing and suction, to represent both the exit and intake flows simultaneously and to vary them independently. Special attention has been paid to conditions relating to transition and to the effects of the jets on downwash at the tailplane; flow visualisation by water injection has been particularly helpful in respect of the latter. Later on, the effects of ground under S.T.O.L. conditions are to be studied. There is an urgent need for more general information on ground effect under such conditions, when considerable lift is originating from both wing pressure lift and the direct jet reaction.

Fundamental investigation of relevant jet mixing and impingement problems at forward speeds is also desirable. Early studies on the development of round jets inclined to the mainstream include unpublished R.A.E. experiments on one inch diameter hot and cold jets ejected normal to the tunnel floor, some Rolls-Royce work and experiments on cold jets at Imperial College[17]. More recently, further experiments were made at the College of Aeronautics on a ¾ in. diameter jet emerging at 45° and 90° to a flat surface in a subsonic mainstream. These included pressure measurements

*For the correlation of experimental results the parameter V_0/V_J might profitably be replaced by the momentum coefficient $C_\mu \equiv MV_J/q_0S$, or $1/C_\mu^{\frac{1}{2}}$, where MV_J signifies the momentum efflux.

over the surface and flow surveys across the jet, but have not yet been published. Similar pressure measurements on an annular jet, with internal and external diameters of 1·2 in. and 2·4 in. respectively, have also been reported by Boulton Paul[13].

The design of inlet and exit louvres for the satisfactory operation of lifting fans at forward speeds is not straightforward, particularly if the louvres are to be of simple and lightweight construction, and to incur no drag penalty in cruise. Early tunnel experiments on inlet flows with single-fan wing models showed that the local velocities into the fan annulus tended to be highest at the upstream end of the hub, the downstream end of the duct, and the side of the advancing blades. A uniform cascade of flat-plate vanes proved disadvantageous at practically all mainstream speeds. A cascade of cambered vanes adjusted to give more turning at the forward end rather than the rear end of the intake offer greater promise*. Inlet problems and intake louvres are now being investigated more fully at N.P.L. on an improved single-fan wing model of unit aspect ratio (Fig. 4). It is intended that similar experiments on fuselage installations should follow. Another practical difficulty relates to the starting of engines or fans in flight when the external pressure at the inlet is lower than that at the exit. Rolls-Royce and Shorts have already devoted attention to this and the general inlet problem in connection with the S.C.1 pure-jet installation and have proposed several interesting solutions.

The rearward deflection of jet flows may be of considerable importance for the provision of thrust during transition or for S.T.O.L. operation, especially with the relatively large intake momentum (sink drag) of fan-lift systems. Although exit cascades can undoubtedly provide large turning angles[10], the effect on fan performance needs to be studied further, and there is scope for much simpler systems possibly making use of deflection by Coanda effect. It is again intended that N.P.L. should investigate such problems on their improved single-fan model, but tests on a multi-jet model would also seem well worthwhile.

2.4. TUNNEL INTERFERENCE

Tunnel interference presents novel and difficult problems when large amounts of air are being ejected from the model at a large angle to the confined mainstream and similar amounts may be simultaneously withdrawn through intakes. The amount of air transferred, possibly up to 10 per cent of the working section flow rate, can generate large flow curvatures about the model, while the jet may approach close to or even impinge on the tunnel floor. Thus, the conventional blockage and lift constraint corrections are no longer adequate and many new aspects have to be considered, as discussed in Section 2 of Ref. 61. At present, in the absence of adequate analysis, no special corrections are normally applied for tunnel interference with round-jet models. Some provisional recommendations regarding limitations on model size to minimise tunnel interference have been put forward in Ref. 61, but these will usually have to be relaxed for models with fans, for constructional reasons. Hence, new theoretical treatments are essential to provide a basis for realistic tunnel interference corrections.

To give some idea of the combined magnitude of such corrections, the multi-fan wing model tested in the R.A.E. 13 ft. × 9 ft. tunnel is undergoing some comparative tests in the larger 24 ft. diameter (open-jet) tunnel. In addition, experimental studies are to be carried out on a simple single-jet model at various heights above the floor and with various ground-board heights. These should provide more accurate guidance on acceptable model dimensions relative to those of the working section, and on the relative importance of clearance from the floor (ground) relative to clearance from the roof and two sides. It must be stressed that removal of the tunnel walls (open-jet) does not preclude interference; even if the conventional wake-blockage corrections become negligible, the free-boundary conditions still restrain the distribution of velocity about the model and, in addition, significant distortion of the boundary shape can itself occur. For simple conventional models, a partially ventilated working section (slotted or perforated walls) offers much reduced lift constraint corrections and small blockage; but the appropriate theoretical correction factors have still to be derived and justified for more elaborate models. Furthermore, these correction factors are particularly sensitive to the assumed effective open area, which may vary significantly from the geometrical value particularly when large amounts of air are being removed or injected into the mainstream. Such problems need much more careful examination theoretically and experimentally to ensure that ventilated walls are practically advantageous for direct jet-lift or more general high-lift testing.

3. Propeller Lift

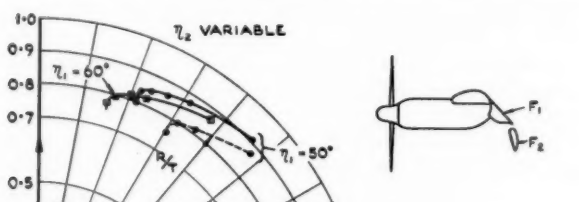
The design of an R.A.E. propeller-lift model for wind tunnel tests at low mainstream speeds was initiated early in 1958, at a stage when the available N.A.S.A. force data was limited to the results of tests on half-models in the static condition. The complete model was intended to provide basic understanding and information on the longitudinal and lateral stability derivatives of aircraft using the tilt wing and deflected slipstream principles for V.T.O.L. and S.T.O.L. By the time the model was built, N.A.S.A. (Langley) were testing complete models, both in the 17 ft. test section of their modified 10 ft. × 7 ft. tunnel and in their 60 ft. × 30 ft. tunnel; the Vertol tilt wing aircraft and several dynamic models had also been flown successfully. However, the R.A.E. model tested by Kirby and Eyre represents a basic four-propeller configuration differing in several aspects from the N.A.S.A. models and was designed to provide data complementary to that from the American tests, as well as essential fundamental information and experience. Furthermore, some experiments were vital to establish satisfactory tunnel techniques and determine model size limitations when representing static and low mainstream speed conditions in the smaller British tunnel facilities, as well as to assess desirable modifications to the R.A.E.

*These have given improvements in model tests by Vertols and N.A.S.A. in the U.S.A.

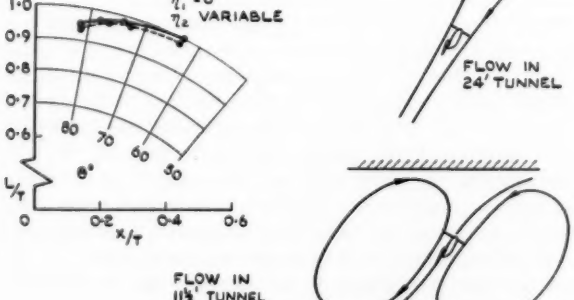
FIGURE 7(*a*). Propeller-lift model. Left, the tilt-wing version and right, the deflected-slipstream model.

24 ft. tunnel equipment for general V.T.O.L./S.T.O.L. model tests.

The complete model (Fig. 7(*a*)) has an aspect ratio 6·5 wing of rectangular plan form and N.A.C.A. 4418 section, mounted high on a fuselage of rectangular cross-section with rounded corners. The underslung propellers are scaled representations of a Rotol design, the two on each half-wing rotating in the same direction and being fitted so as to oppose the relevant wing tip vortex. The tilt-wing version has tilt angles of 20°, 40°, 60° (90° later) about a pivot point at 0·6 chord, and a single slotted flap of variable angles. The deflected slipstream version uses the well-tried N.A.S.A. arrangement of a sliding front flap and a slotted rear flap of variable angles fitted to the fixed wing. Six alternative tailplane heights are provided for downwash measure-



DEFLECTED SLIPSTREAM CONFIGURATION



TILT WING CONFIGURATION ($\alpha_{TILT} = 60°$).

FIGURE 7(*b*). Static tests.

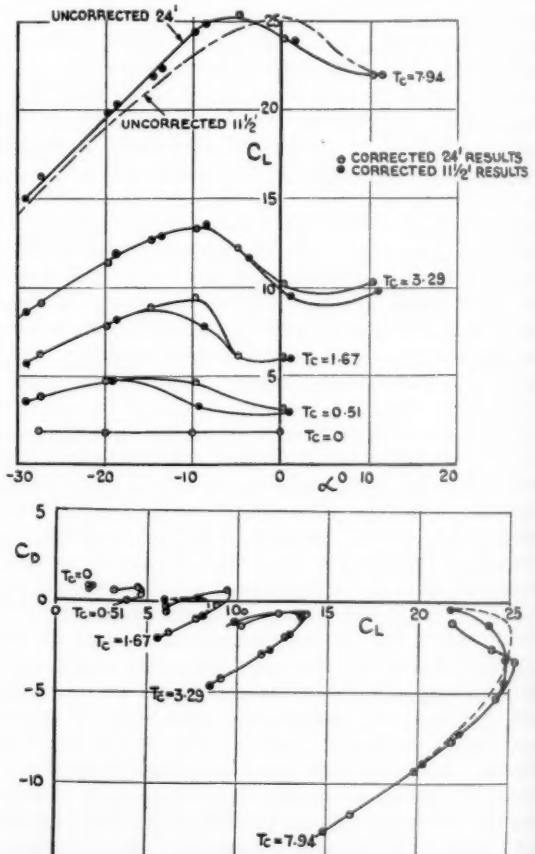


FIGURE 7(*c*). Deflected slipstream configuration. ($\eta_1 = 50°$, $\eta_2 = 40°$). Lift and drag coefficients.

ments, four on a flat-plate fin and two on the fuselage, and a conventional fin is fitted for lateral stability tests.

Preliminary tests were first made at the end of 1958, on an isolated propeller nacelle combination, to find the optimum blade angle (10° at 0·7 radius) for the static and low forward speed conditions which would have to be represented on the complete model, and to find the maximum r.p.m. (9,000) acceptable without undue motor heating. For the static tests on the complete model, the maximum thrust was fixed at 15 lb. (8,700 r.p.m.), corresponding to a developed slipstream velocity of nearly 100 ft./sec. The forward speed conditions were represented by running the propeller at about 8,700 r.p.m., keeping the advance ratio $J\,(=V_0/nD)$ constant as the ambient conditions changed and as the wing tilt or flap deflections were varied at a given nominal tunnel speed. The tunnel speed was also varied from 20 to 60 ft./sec., the slipstream dynamic pressure (q') remaining sensibly constant, while the thrust coefficient $T_c''[\equiv 4T/q''\pi D^2]$ varied from 0·95 to 0·6 and $T_c[\equiv T/2q_0D^2]$ from 7·9 to 0·5.

The first longitudinal force measurements for the tilt-wing configuration, with 60° tilt angle, agree well for the two tunnels both under static and forward speed conditions. This occurs despite large differences in the air flow close to the model when the mainstream speed is zero or low (Fig. 7(*b*)). For the deflected-slipstream configuration, the 6 ft. span model with 1·3 ft. propeller diameter appears too large for tests in the 11½ ft. × 8½ ft. tunnel for tunnel mainstream speeds below about 20 ft./sec. (15 knots full-scale). The primary effect of the constraint of the smaller tunnel is to cause a premature separation of the flow over the forward flap in static and very low forward speed conditions. Thus, in the static case, the maximum angle through which the flow can be turned by the flaps is reduced from 75° in the 24 ft. diameter tunnel to 60° in the 11½ ft. × 8½ ft. tunnel (Fig. 7(*b*)). The resultant force/thrust ratio is in both cases 0·8 at these maximum angles. Typical comparative results from the two tunnels at forward speeds of 20 to 60 ft./sec. are shown in Fig. 7(*c*). The corrected curves* for the 11½ ft. × 8½ ft. tunnel agree well with those from the 24 ft. tunnel (negligible corrections), except beyond the stall where the difference in mainstream turbulence levels can have a significant effect. In fact, for tunnel speeds of 30 ft./sec. or more ($T_c < 3{\cdot}3$) the uncorrected curves are not far different, because the velocity and lift-constraint corrections are not only opposite in sign but also roughly of the same magnitude.

As regards operation of the 24 ft. tunnel with the propeller-lift model present, steady mainstream flow has been maintained as low as 20 ft./sec., but a core of higher velocity air from the propeller slipstream tended to circulate round the return circuit of the tunnel. Methods of running at even lower speeds and of precluding circulation of such high velocity cores are to be examined. The existing overhead three-component balance proved reasonably accurate, but somewhat tedious and tiring to operate. New equipment to facilitate force measurement (six-components) is required, and possible strain-gauge model balances should be considered. For the present, it is hoped that the smaller tunnels with their six-component balances and capacity for economic running can suffice for much of the main programme on V.T.O.L./S.T.O.L. models. But it is expected that the 24 ft. tunnel will have to be used for many check tests at the lower and zero forward speeds, and improvements to this tunnel and its associated equipment are certainly required.

*The corrections include the conventional allowance for the presence of slipstream on mainstream speed, for the upwash arising from lift-constraint (taken at zero propeller thrust) and also for the delay in stalling angle with the highly turbulent slipstream.

4. Jet Flaps

4.1. GENERAL COMMENTS

British jet-flap studies were started at the N.G.T.E. towards the end of 1952, in an attempt to integrate fully the propulsive and lifting systems of turbo-jet aircraft and thereby provide S.T.O.L. performance without penalising the cruising performance[18]. The pioneer investigations throughout 1953 included first studies of the basic concepts and mechanism[19, 20] accompanied by two-dimensional pressure-plotting experiments on simple small-scale models[21] at N.G.T.E., together with complementary three-dimensional experiments[22] at N.P.L. to ascertain the importance and order of magnitude of finite aspect ratio effects. About the same time, the first rigorous theory for the two-dimensional jet-flap aerofoil in inviscid flow was proposed[30]. Unfortunately, owing to urgent demands for research on other high-lift schemes more elaborate and extensive investigations on jet-flaps proceeded slowly until 1957, though by that time the basic aerodynamic principles for both two-dimensional[21, 31, 32] and three-dimensional[22, 34] jet-flap wings had been well established (*see* Ref. 41). Since then, experimental and theoretical work has been intensified on basic stability and control as well as lift and thrust aspects.

4.2. WIND TUNNEL EXPERIMENTS

To follow up the exploratory pressure-plotting tests[21, 22, 23], comprehensive force measurements and flow studies were made at N.P.L.[24] (1957) on a rectangular-wing half-model of aspect ratio 6† with a body (Fig. 8(*a*)). The wing had a 12 per cent thick section with blowing over a 10 per cent chord trailing edge flap whose deflection could be readily varied between 0° and 90°. Lift, pitching moment and thrust measurements were completed for values of the sectional momentum coefficient $C_\mu'[\equiv MV_3/q_0S']$ up to 2·5; the overall momentum coefficient $C_\mu \equiv S'C_\mu'/S = 0{\cdot}9C_\mu'$ for the majority of the tests, when the blowing slot and flap extended from the wing root to wing tip. Mean downwash was also determined using a tailplane of variable incidence and height at a conventional fore-and-aft location. Confirming the earlier pressure plotting results, the total lift C_L represented a considerable magnification of the corresponding vertical component

†Although the aspect ratio of this model could be varied to 3 and 9, such tests were unfortunately never made.

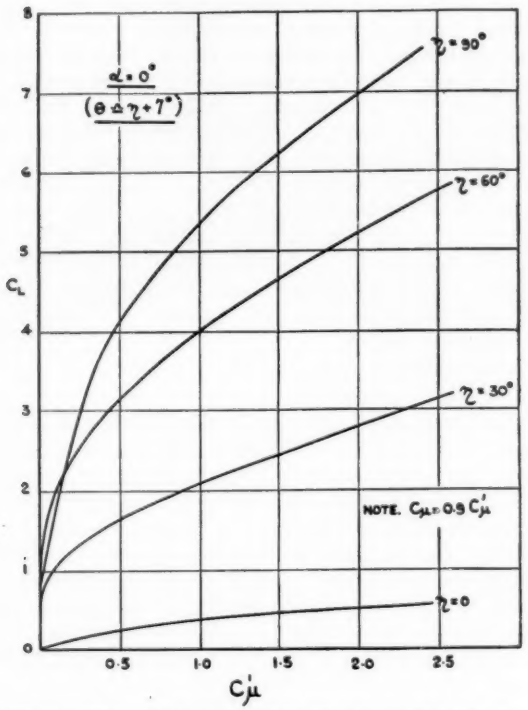


FIGURE 8(*b*). Rectangular-wing jet-flap model. Variation of lift with momentum coefficient.

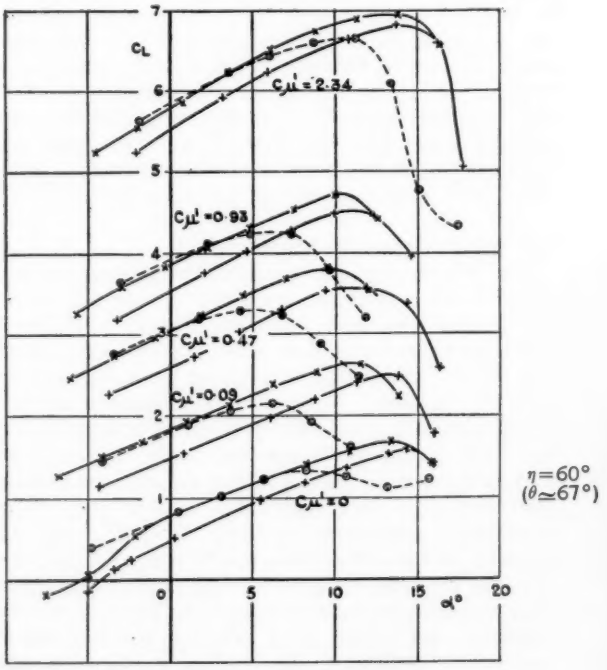


FIGURE 8(*d*). Rectangular-wing jet-flap model. Effect of leading edge droop and trailing edge flap chord.

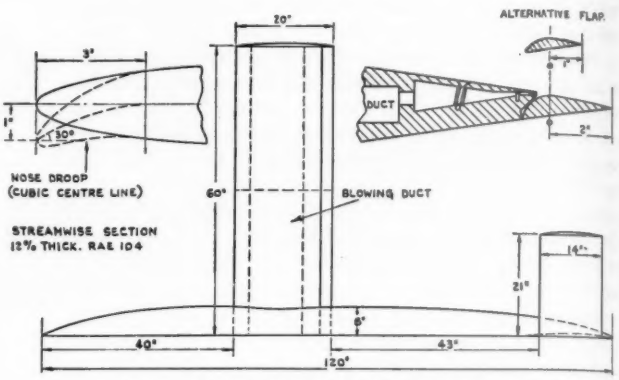
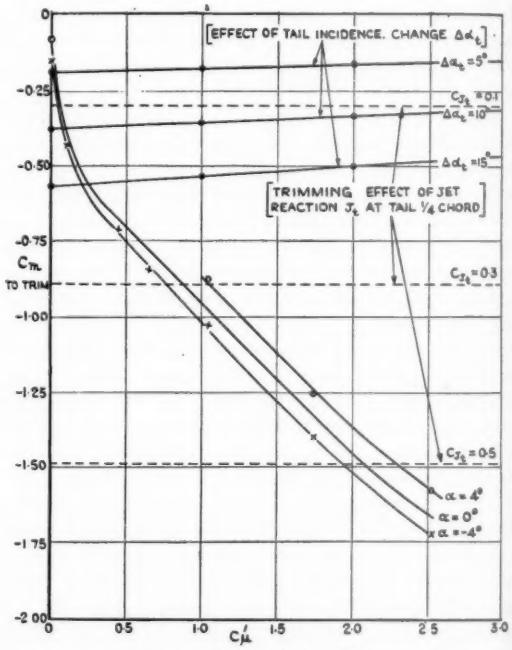


FIGURE 8(*a*). Half-model of jet-flap rectangular wing.



c.g. at 0·35*c*, $h_t/c = 1·2$
$\eta = 60°$, $(\theta \simeq 67°)$

FIGURE 8(*c*). Rectangular-wing jet-flap model. Pitching moment to trim with zero tailplane lift.

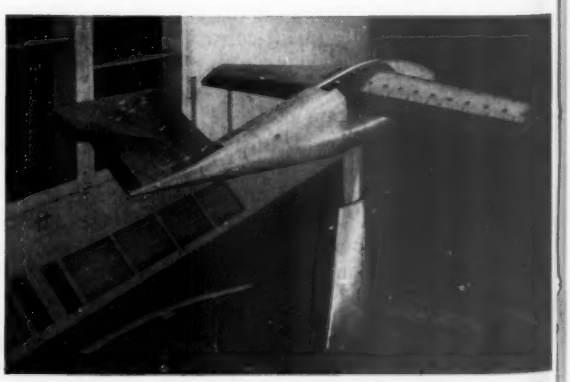


FIGURE 9(*a*). Jet-flap complete model (aspect ratio 6 version).

$C_\mu \sin(\theta+\alpha)$ of the jet momentum; for example, $C_L=5{\cdot}4$ at $\alpha=0$ and $\theta=67°$ with $C_\mu=2$ (*see* Fig. 8(*b*)). The centre of lift, located at about half-chord for low C_μ values, tends to move farther rearwards with increasing C_μ at constant wing incidence and flap angle. The amount of trimming feasible with a conventional tailplane appears totally inadequate for practical c.g. positions, but auxiliary trimming jets at the tail could reasonably be used (*see* Fig. 8(*c*)) or possibly blowing on the tailplane itself*. Downwash of as much as 20° was measured in the vicinity of the tail position for C_L values of the order of 7. The sectional thrust coefficient

$$C_{X\infty} \equiv \frac{S}{S'}\left[C_X + \left(\frac{C_L^2}{\pi A + 2C_\mu}\right)\right]$$

derived by making a theoretical allowance for the trailing vortex drag (*see* Section 4.4) was about $0{\cdot}83C_\mu'$ up to $\theta=37°$ decreasing slowly to about $0{\cdot}6C_\mu'$ at $\theta \simeq 60°$ and $0{\cdot}25C_\mu'$ at $\theta \simeq 90°$. These N.P.L. experiments also examined the effects of variations in the spanwise extents of the blowing slot and trailing edge flap on lift, pitching moment and thrust.

More recently, research on this rectangular-wing model has been continued at the R.A.E.[25], with particular attention to the alleviation of flow separation over the nose of the 12 per cent thick aerofoil section, and to the effect of trailing edge flap alignment and size on thrust. The nose separation, which developed even at small incidence for large flap deflections, was delayed about 5° by the incorporation of a drooped leading edge (*see* Figs. 8(*a*) and 8(*d*)). In practice, wing nose boundary layer control would be more powerful and profitable on such a section, either within the first 2 per cent chord from the wing leading edge as already demonstrated on a small-scale research model[23], or at the knee of a leading edge flap. Careful alignment of the upper surface of the trailing edge flap knee with the lower boundary of the jet, instead of the upper boundary, raised the sectional thrust coefficient $C_{X\infty}$ by about $0{\cdot}03\,C_\mu'$ at small flap angles. On the other hand, reduction of the flap chord from $0{\cdot}10c$ to $0{\cdot}05c$ raised the sectional thrust coefficient by only about $0{\cdot}01\,C_\mu'$. The decrease in C_L value at various flap angles was almost independent of the C_μ value and incidence (*see* Fig. 8(*d*)), roughly corresponding to the change to be expected from trailing edge flaps with attached flow. Further thrust investigations are to be made with blowing from the wing trailing edge itself, the slot lip thickness and slot blockage being varied. All the jet-flap thrust results will then be analysed in the light of comparative static thrust measurements on several round nozzles with their internal and external shape varied. It would seem that the ratio $C_{X\infty}/C_\mu'$, for blowing over a simple plain flap is unlikely to reach much more than 0·92† even at small angles and with improvements to the slot internal geometry, compared with about 0·97 for a conventional round nozzle. The remaining difference of about 5 per cent appears to arise mainly from high skin friction over the flap upper surface; exploratory studies indicate that a small gap between the flap nose and shroud could be beneficial, since this permits mixing of the mainstream air at the lower boundary of the high velocity jet before it reaches the flap surface.

As a preliminary investigation of the effects of high sweep and low aspect ratio on jet-flap wings, three-component measurements were made at the N.P.L. on a half-model of a 60° delta wing with the air ejected over a part-span flap[28]. Despite magnification of the direct jet-reaction lift by more than two, up to the highest C_μ value (1·5) tested, the experiments were not followed up because of the large negative thrust (high "trailing vortex" drag) which occurred other than at low lifts and jet deflection angles. However, the usefulness of moderate C_μ values for control purposes on low aspect ratio wings should not be overlooked.

Six-component force tests on a complete model (Fig. 9(*a*)) have been made at the R.A.E.[27] to provide basic information on stability derivatives in sideslip, first without ground and later with various ground heights. The initial version of the model had an unswept wing of aspect ratio 6 with negligible dihedral. The longitudinal force measurements at zero sideslip substantiated those from the N.P.L. rectangular-wing half-model, except as regards stalling incidence and maximum lift coefficient, since the use of thick and highly cambered wing section (N.A.C.A. 4424) successfully reduced flow separation over the wing nose at high lift coefficients. For example, the stalling incidence ($\partial C_L/\partial\alpha=0$) rose to at least 30° with $C_\mu>1$, while untrimmed C_L values of about 7 and 9 were reached at 0° and 30° respectively for $C_\mu=3$ with a jet angle of 80°. Admittedly, the loss of lift at the stall became more severe, but this is hardly surprising when the flow is maintained unseparated by the thick wing and jet induction effects up to such high lift coefficients.

The influence of geometrical changes in wing aspect ratio, dihedral and sweepback were investigated, primarily with regards to the lateral stability (as discussed later), but the effects on lift and thrust are also worth noting. An increase in aspect ratio to 9, by the addition of wing tip extensions, raised the lift coefficient appreciably for a given C_μ (Fig. 9(*b*)) though it must be remembered that the rise for a prescribed installed momentum will be much less. The thrust to lift ratio C_X/C_L was increased as expected due to the reduced "trailing vortex drag", but the ratio $C_{X\infty}/C_\mu'$ remained virtually unchanged. The addition of 5° dihedral had negligible effect, but the addition of 10° sweepback tended to reduce not only lift and stalling incidence (Fig. 9(*b*)), but also the thrust/lift ratio.

Early on, during the investigation of sideslip effects on the aspect ratio 6 version, some positive l_v values (anhedral effect) were unexpectedly found at high jet deflection angles and lift coefficients. When the aspect ratio was increased, the trend towards large positive l_v became accentuated (Fig. 9(*c*)) and was highly undesirable from the standpoint of spiral instability*. This

*A canard layout is of course attractive with regard to the effects of trim on overall lift.

†As usual, the momentum coefficient is assumed to be specified in terms of the measured mass flow rate M and the theoretical velocity V_J corresponding to isentropic expansion from the slot (or nozzle) total pressure to the mainstream static pressure.

*For spiral stability $l_v n_r - n_v l_r > 0$.

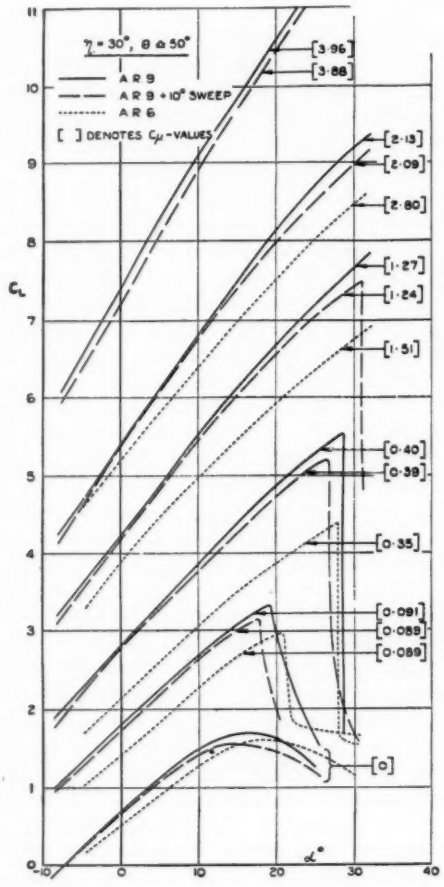


FIGURE 9(*b*) (*left*). Jet-flap complete model. Effect of variation of aspect ratio and sweep.

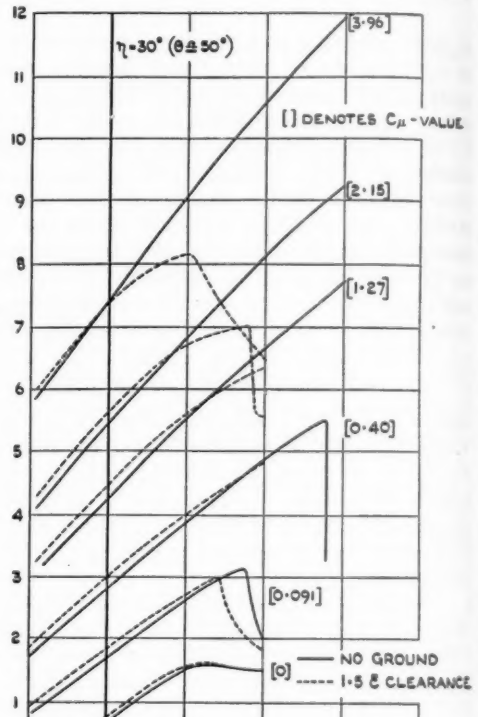


FIGURE 9(*c*) (*right*). l_v for jet-flap complete model. Effect of changes in aspect ratio, dihedral and sweep.

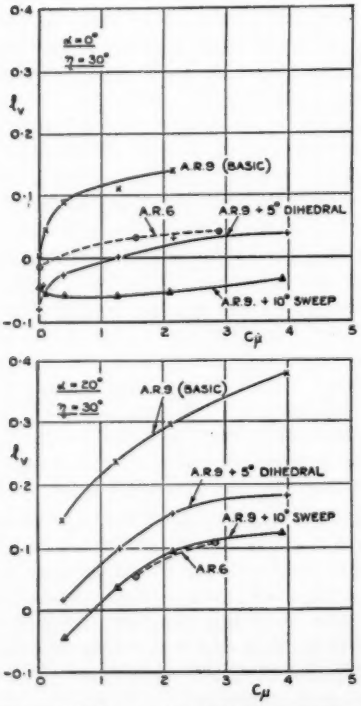


FIGURE 9(*d*). n_v for jet-flap complete model. Effects of changes in aspect ratio, dihedral and sweep.

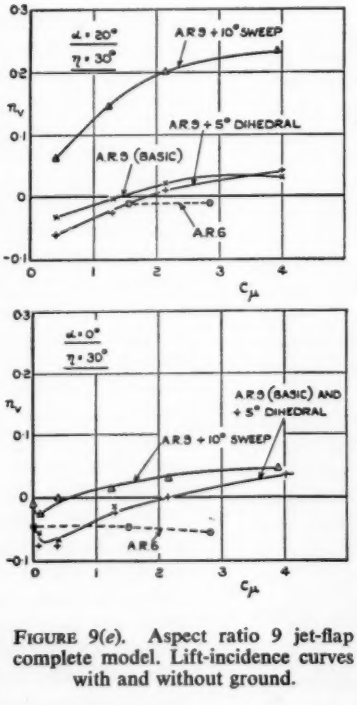


FIGURE 9(*e*). Aspect ratio 9 jet-flap complete model. Lift-incidence curves with and without ground.

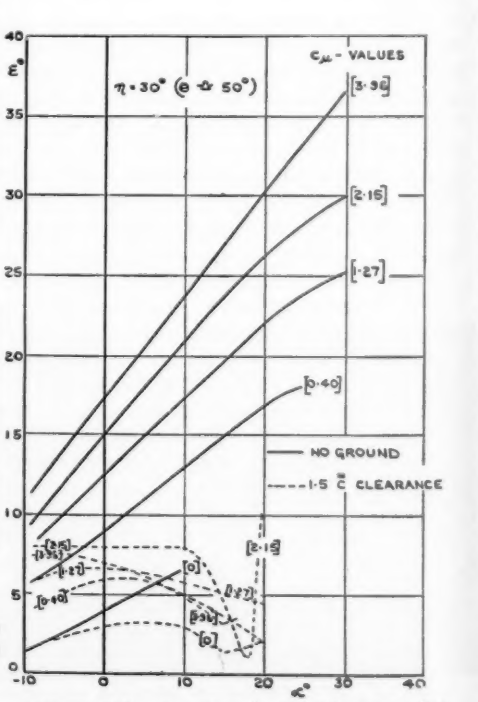


FIGURE 9(*f*). Aspect ratio 9 jet-flap complete model. Downwash curves with and without ground.

tendency was considerably alleviated by dihedral and sweepback but, in contrast to conventional arguments, the change due to sweep did not increase steadily in magnitude with C_L. Furthermore, sweepback caused substantial sidewash effects on the fuselage and fin thus increasing n_v (Fig. 9(*d*)) and $-y_v$ at high C_L values. These experiments have provided essential basic information and understanding for the determination of stability derivatives and associated tailplane and fin effectiveness, and for the revision of inadequate conventional theoretical treatments (*see* Section 4.4). Further tests are planned on the model to separate out the force contributions on the wing and body. Measurements of at least one damping derivative, probably the damping in yaw n_r, are also to be made under oscillatory conditions as a check on existing quasi-steady treatments.

The possibility of adverse effects of ground proximity on the lifting effectiveness of jet-flap wings was appreciated quite early on[21]. Detailed two-dimensional tests on ground effect were therefore undertaken at Southampton University[28], using the early N.G.T.E. and N.P.L. pressure-plotting aerofoils with trailing edge blowing at 30° and 60° to the chord line. The pressure lift on the aerofoil was found to reach a maximum, at a C_μ value increasing with greater ground clearance or smaller jet angle, when the jet completely blocked the mainstream flow between the lower surface of the wing and ground. As the C_μ value was raised further, a vortex formed below the wing, generating a downward suction force on the rear lower surface. This not only kept the total lift substantially constant, by reducing the pressure lift, but also caused nose-up changes in the pitching moment. Typically, at a ground clearance of one chord, the ground effect was negligible at 30° jet angle, but the total C_L barely rose above 6 for a jet angle of 60°.

The effect of ground is now being investigated on the unswept aspect ratio 9 version of the R.A.E. complete model, to determine changes in longitudinal and lateral stability derivatives as well as lift and thrust. Six-component force measurements have already been completed with a ground clearance H of about $1{\cdot}5c$. Significant reductions in lift-incidence curve slope occurred as the C_μ value (or θ) was raised, together with a much earlier stall as the jet impinged on the ground (Fig. 9(*e*)). This was accompanied by a substantial reduction in thrust and a tendency to pitch-up (tail-off). Furthermore, large reductions in the downwash angle at the tailplane position would appear to present a major problem arising from proximity of the jet to the ground (Fig. 9(*f*)). Fortunately, the lateral stability derivatives are less seriously affected until the jet actually impinges on the ground; then, although negative changes (dihedral effect) tend to occur in l_v, there are considerable reductions in n_v, $-y_v$, and fin effectiveness. Further force measurements and flow studies are now being carried out to provide some guidance on the rate of variation with height, and on the mechanism of the earlier stall.

4.3. TUNNEL INTERFERENCE

The problem of tunnel interference corrections for jet-blowing models has already been touched on in Section 2, and those for jet-flap models in particular are discussed at some length in Ref. 61. Wake-blockage corrections are now available for completely stalled as well as fully attached flows, but those for bubble-type flows with re-attachment ahead of the trailing edge are far from certain. Again, apart from such low velocity wakes, consideration is also necessary of the high velocity plane-jets which are being fed into the tunnel mainstream, possibly with a ground board comparting the tunnel.

As regards lift constraint corrections, the conventional treatments cannot be assumed adequate because of the existence of the powerful jet sheet downstream of the trailing edge. For two-dimensional models, alterations in the stream curvature over the aerofoil chord and in the curvature of the jet sheet itself need to be taken into account, but a detailed mathematical treatment of this problem has not yet become available. For finite aspect ratio models, the effects on stream curvature over the wing chord can probably be neglected as usual, but the images associated with the trailing vortex system can cause significant alterations in the curvature of the jet sheet. The appropriate lift constraint corrections, for thin full-span jet-flap wings in an inviscid mainstream, have been derived in Ref. 29 as an increment $\Delta\alpha$ to the geometrical wing incidence α, together with an increment ΔC_μ to the jet momentum coefficient C_μ. Additional problems arise when the jet momentum coefficient and angle, or wing chord and incidence, are so large that the distribution of vorticity can no longer be assumed to lie along the tunnel centre line. Again, proximity of the jet sheet to the tunnel floor, or impingement, can be especially significant (except for true ground representation) since the jet then imposes gross constraints on the mainstream. In the absence of adequate corrections, the model size may have to be severely limited[60, 61].

4.4. THEORETICAL INVESTIGATIONS

Theoretical treatments for infinitely thin *full-span* jet-flap wings ($S'=S$) in inviscid flow were developed at the R.A.E. about three years ago, being analogous to those of mean-line theory for aerofoil sections[32, 33] and classical "lifting line" theory for finite aspect ratio effects[34]. The lift is then determined by the relation

$$C_L=[\eta\,(\partial C_L/\partial\eta)_\infty+\alpha\,(\partial C_L/\partial\alpha)_\infty]\,F\,(A,C_\mu)$$

where the sectional derivative $(\partial C_L/\partial\eta)_\infty$ is purely a function of C_μ and the flap chord ratio c_f/c, and $(\partial C_L/\partial\alpha)_\infty$ is identical with $(\partial C_L/\partial\eta)_\infty$ for $c_f/c=1$, as plotted in Fig. 10. The function

$$F\,(A,C_\mu)=\frac{A+(2C_\mu/\pi)}{A+2+0{\cdot}604C_\mu^{\frac{1}{2}}+0{\cdot}876C_\mu}$$

represents a finite aspect ratio factor. The thrust coefficient becomes

$$C_X=C_\mu-[C_L^2/(\pi A+2C_\mu)],$$

where the last term represents a "trailing vortex" drag associated with finite aspect ratio effects, for the assumed spanwise variation in wing geometry and jet momentum (to give uniform downwash).

Despite the linearised nature of these theories, the

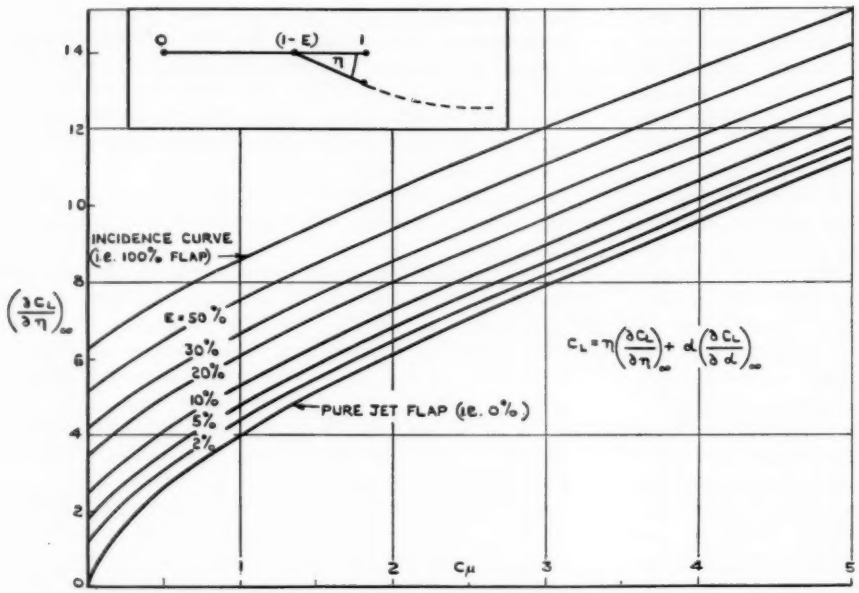


FIGURE 10. $\partial C_L/\partial\eta$ for thin aerofoil with trailing edge flap blowing.

Some simple theoretical arguments to explain ground effects have been put forward for conditions when the jet is sufficiently strong and inclined to block the mainstream flow between the lower surface of a two-dimensional aerofoil and the ground[39, 40]. However, more representative mathematical models are desirable, together with treatments of the more general problem for three-dimensional jet-flap wings and for jets in proximity to, but not impinging on, the ground.

lift predictions agree quite well with experimental results for full-span trailing edge blowing up to C_μ values of 2 and jet angles of 60°, if a correction factor $(1+t/c)$ is applied to the pressure-lift component to allow for finite thickness effects. However, considerable difficulties arise in applying them to the case of part-span blowing or deflection[24]. Furthermore, the predicted value of the thrust corresponding to inviscid flow markedly over-estimates the measured values, especially for jet angles exceeding 30° (*see* Section 4.2), primarily because of losses due to skin friction and violent mixing near the jet exit in the practical case. This theoretical treatment can also be used to predict pressure distributions as well as overall forces, in a similar way to Glauert's theory for the hinged flat plate. A separate method has also been devised for evaluating the pressure distribution taking into account thickness and camber effects, but this requires the lift and thrust to be initially specified[35].

The foregoing theoretical treatments have been further developed and applied for the estimation of downwash[36] with finite aspect ratio jet-flap wings, rotary lateral stability derivatives[37], and longitudinal stability and control[38]. More recently, experimental measurements of steady state lateral stability derivatives showed that conventional estimates of the rolling moment derivative l_v due to sideslip could be considerably in error, with regard to the basic plan form and sweepback contributions. A modified theory was devised to allow for the presence of the strong trailing vortex sheet and the unusual chordwise distribution of bound vorticity. This gave substantially better agreement, but it is still difficult to predict accurately the effects of wing position, camber, incidence, flap angle and C_μ on l_v. Again, as regards the yawing derivative n_v and side-force derivative y_v due to sideslip, the effects of the substantial sidewash changes associated with sweep may be difficult to estimate.

5. Boundary Layer Control

5.1. GENERAL COMMENTS

British research on boundary layer control for the prevention of separation, as a means of improving $C_{L\,max}$ or the largest usable lift coefficient, has been mainly associated with configurations appropriate to high speed aircraft, with a view to ensuring acceptable landing and take-off performance. However, much of the knowledge and experience gained is applicable to a far wider range of configurations, especially as regards S.T.O.L. considerations. It has long been established that trailing edge flap effectiveness can be much improved at large angles by blowing or suction, yielding higher lift increments at constant incidence and hence larger $C_{L\,max}$ without undue mechanical complexity. Likewise, the stalling (or pitch-up) incidence and $C_{L\,max}$ have been substantially increased by nose blowing or nose suction, offering an attractive alternative or supplement to mechanical leading edge devices. Wing trailing edge flap boundary layer control and wing nose boundary layer control have come to be regarded as complementary rather than competitive, since the benefits of powerful trailing edge flaps cannot be fully realised unless attached flow over the wing nose is sensibly ensured. On the other hand, the relative merits of blowing tangentially from a narrow slot, blowing at a large angle to the surface through small holes, suction through a narrow slot, or suction through a porous area are largely dependent on the type of aircraft application envisaged and the most convenient source of pumping power available.

5.2. TRAILING EDGE FLAP BLOWING

The main research programme on slot-blowing for boundary layer control over trailing edge flaps was completed by 1957 (*see* Ref. 43). Wind tunnel experiments have been carried out on a range of simple plan forms and of specific aircraft layouts, comprising a

variety of aspect ratios, leading edge and trailing edge sweeps, flap spans and blowing arrangements. The models included an 8 per cent thick aerofoil[46] (Fig. 11(*a*)), a 5 per cent thick 60° delta[47], an untapered 55° swept-back wing, the de Havilland Sea Venom[48] and Sea Vixen[51], the Supermarine Scimitar[49], the Saunders-Roe P.177[50] and the Blackburn N.A. 39[52] (Fig. 12); even this list is not complete as regards work outside Government establishments. The initial experiments of Refs. 46 and 48 provided the essential understanding; for example, the variation of lift, nose-down pitching moment and drag with C_μ was satisfactorily interpreted and related to the modifications in the surface flow and pressure distributions. Supersonic blowing (choked slot) and subsonic blowing results correlated remarkably well on a C_μ basis, confirming that with increasing pressure ratios smaller mass flows and duct velocities would be needed. The subsequent model tests also provided adequate confirmation that sectional C_μ' values of 0·01, 0·02, 0·04 and 0·07 should suffice, with a well-designed system, to prevent flow separation at trailing edge flap angles of 30°, 45°, 60° and 75° respectively; at least for hinge line sweeps up to 30°, leading edge sweeps up to 60° without extensive leading edge flow separation, and flap chords up to 30 per cent wing chord. Although knee blowing proved slightly better than shroud blowing at large flap angles, the choice in practice is likely to depend more on structural than aerodynamic advantages.

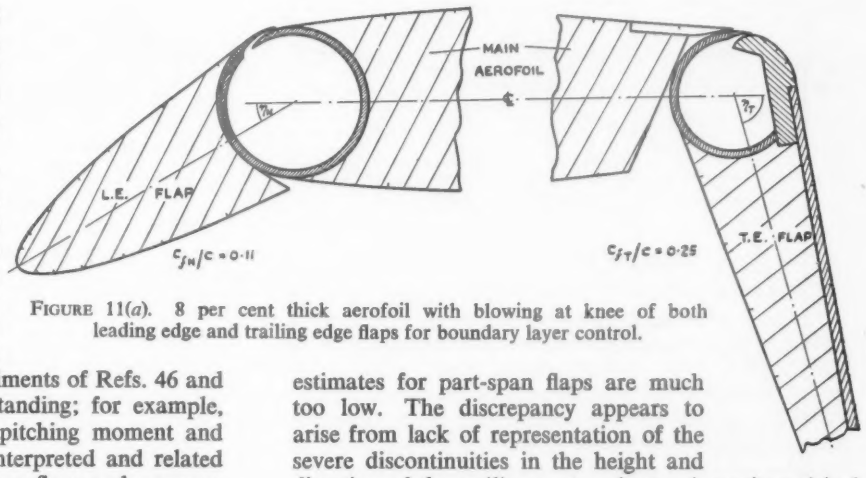


FIGURE 11(*a*). 8 per cent thick aerofoil with blowing at knee of both leading edge and trailing edge flaps for boundary layer control.

Some experimental and theoretical work is still in progress on the fundamental mechanisms associated with blowing tangential to the surface to prevent separation of the turbulent boundary layer under severe adverse pressure gradients. The basic problem of the so-called Coanda effect[58], by which the jet itself clings to a highly curved surface, has been studied at the N.P.L. and the College of Aeronautics but the analysis of results has not yet become available. The more general problem with mainstream as well as jet-flow is also being examined at the N.P.L. using simple flap blowing models, to establish a method of calculating the development of the turbulent wall jet under such conditions.

Methods of predicting the sectional lift and pitching moment increments for trailing edge flaps with boundary layer control were initially based on linearised theory for a hinged flat plate, being extended to finite wings by arguments based on "simplified lifting surface theory"[45]. Later improvements of the methods[44, 48] include the use of exact theory for the hinged flat plate at large angles[52] and of jet-flap theory (Section 4.4) to allow for super-circulation effects when the sectional momentum coefficient C_μ' exceeded the values C_{μ_∞}' for attached flow. Although useful drag estimates can be made for full-span flaps, using the simplified lifting-surface theory for the "trailing vortex" drag, similar estimates for part-span flaps are much too low. The discrepancy appears to arise from lack of representation of the severe discontinuities in the height and direction of the trailing vortex sheet. A semi-empirical approach has been tentatively suggested[44, 48], but more theoretical treatments need to be devised.

Full-scale flight investigations on trailing edge flap blowing were first carried out with a Hawker Hunter[43] and a de Havilland Sea Venom[54, 43] both at the respective firms and at the R.A.E. These modifications of existing service aircraft were intended primarily to provide constructional experience in developing full-scale blowing systems, together with flight research on the effectiveness of blowing for improving landing and take-off performance and on stability and control under such conditions. The existing split flaps of both aircraft were replaced by plain flaps, with shroud blowing on the Hunter and knee blowing on the Sea Venom. These practical investigations demonstrated clearly that full-scale installation of flap blowing was feasible, that careful attention to detail design would be well worthwhile from a performance aspect, and that many difficulties could be avoided if the aircraft were designed with flap blowing in mind right from the outset. On the Supermarine Scimitar, slotted flaps with shroud blowing were incorporated at an early stage in its development, replacing the double-slotted flaps of the first prototype[55]; in 1958, production versions of this aircraft went into regular service with the Royal Navy. More recently, the Blackburn N.A.39 prototype of a naval strike aircraft, which was designed with both trailing edge flap and wing nose blowing right from the outset, also flew successfully with blowing in operation[56].

This flight experience on turbo-jet aircraft has demonstrated that the improvements in landing approach speed (and distance) feasible with trailing edge flap blowing can depend on many factors other than mere proximity to the stall or $C_{L\,max}$, as discussed in Refs. 59 and 43. For example, a large *increase* in the "zero-lift drag contribution" to drag has been found to occur with blowing over *part-span* flaps, giving a favourable effect on speed stability. Also a change in throttle setting can affect not only the engine thrust but also the wing lift and drag. Because of the increased nose-down pitching moments associated with the more powerful trailing edge flaps, the tailplane volume will need to be

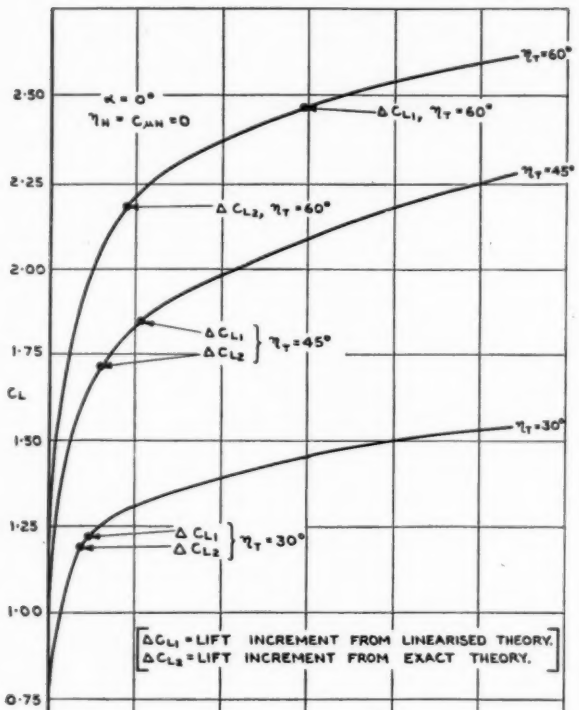


FIGURE 11(*b*). 8 per cent thick aerofoil ($A = 3{\cdot}3$) with trailing edge flap blowing for boundary layer control.

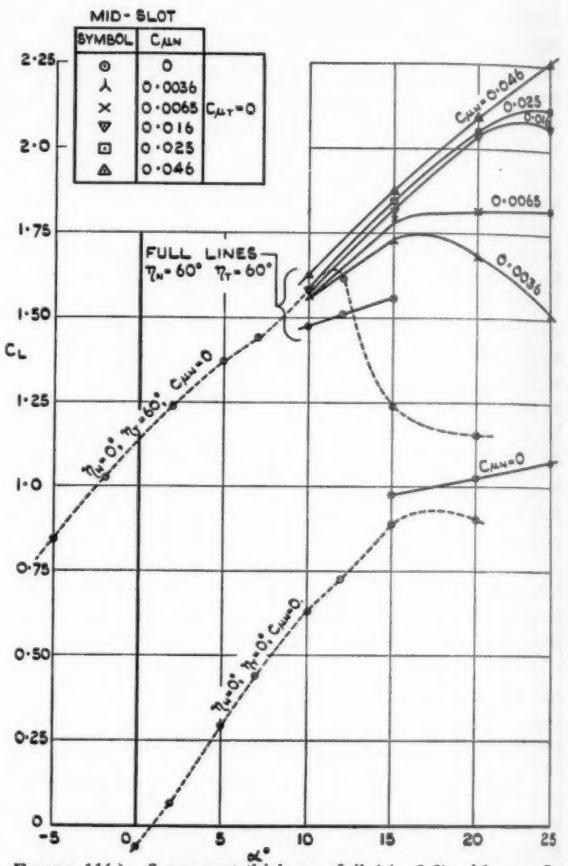


FIGURE 11(*c*). 8 per cent thick aerofoil ($A = 3{\cdot}3$) with nose-flap blowing for boundary layer control.

larger than normal to avoid tailplane stall in the trimmed condition. As regards aileron effectiveness and lateral stability, there is evidence of some slight improvement with flap blowing on swept-back wings.

5.3. WING NOSE BLOWING

Nose-slot blowing was investigated on a 12 per cent aerofoil at the N.P.L.[23] (1954); also, on a moderately swept thin wing at Blackburn Aircraft Limited and later at R.A.E.[52] (Fig. 12) with the slot located in turn at 5, 2, 1 and $\frac{1}{4}$ per cent chord. These experiments established that the optimum chordwise position of the slot lies within the first one per cent chord on moderately thick or thin wings, since the adverse pressure gradients begin practically at the leading edge under high-lift conditions, unless the nose shape has an appreciable radius and camber. Subsequently, tests were made on an 8 per cent thick aerofoil at the N.P.L. with the slot located at the knee of a deflected leading edge flap (Fig. 11(*a*)); this scheme was intended to ease the practical problem of slot installation, as well as to reduce the blowing momentum requirements since the adverse pressure gradients should be smaller at the flap knee. The optimum flap position was shown to be about half-way round the curved knee, when the stalling incidence was raised more than 10° with a C_{μ}' value of only 0·015 (Fig. 11(*c*)). These and other experiments have clearly established nose-blowing to be practicable and profitable for increasing the maximum lift or largest usable lift coefficient of wings up to 60° leading edge sweep.

Inclined air jets have been studied since 1952 by Australian research workers, and more recently in this country. On thin aerofoils, one spanwise row of holes is located on the lower surface, just forward of the stagnation point; this accelerates transition of the boundary layer at the nose by the diffusion of small scale turbulence, thereby reducing the size of the laminar separation bubble to negligible proportions. A second row is then located on the upper surface, just aft of the suction peak, to delay turbulent separation by the promotion of intense turbulent mixing. Wind tunnel experiments have been completed at A.R.L. (Australia) on 6 per cent thick wings both unswept and with 50° sweepback, and at the N.P.L. on a 9 per cent thick wing of about 35° sweepback. The blowing quantities and pressures associated with this scheme are in general smaller than those for tangential slot blowing, but the feasible gains are correspondingly lower. For completeness, it should be noted that inclined air-jets have also proved useful for delaying turbulent separation at the rear of a thick aerofoil and at the knee of a trailing edge flap with up to 20° deflection.

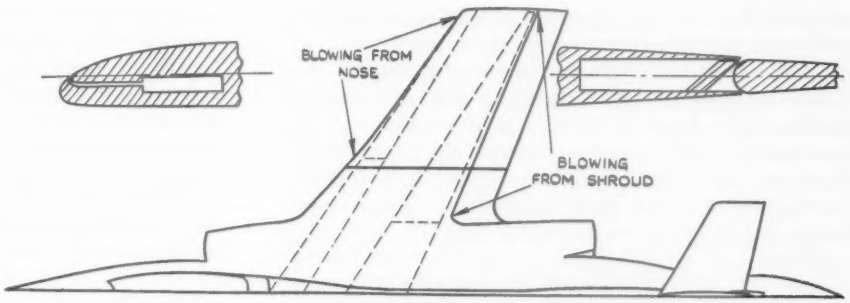


FIGURE 12. Half model of Blackburn N.A.39 with trailing edge flap and wing nose blowing for boundary layer control.

5.4. SUCTION

The aerodynamic effectiveness of suction through slots and porous areas, as a means of providing boundary layer control for high lift, has long been proved by both wind tunnel and theoretical studies. Most of the results have been fully reported and discussed elsewhere[42, 44], so only the major conclusions will be mentioned here. During the past five years, little research has been carried out in this country on suction for high lift, as distinct from low drag, largely because the available effort has been devoted to blowing investigations. No flight experiments have yet been made*, but some are about to be undertaken by Cambridge University with suction through perforated surfaces on a small research aircraft, sponsored by the Ministry of Aviation and built by Marshalls' Flying School Limited.

Research on suction at the knee of a trailing edge flap has been limited to basic experiments, mostly at the N.P.L., with area suction on an 8 per cent thick aerofoil and slot suction on a specially designed 30 per cent thick aerofoil. Flow separation over the trailing edge flap on thin aerofoils seems best prevented by starting area suction about mid-way round the curved surface of the flap knee (minimum pressure point), ensuring a nearly uniform chordwise distribution of the suction inflow velocity V_s. For appreciable flap angles ($\simeq 60°$), the chordwise extent needs to be about 3 per cent of the aerofoil chord and the ratio V_s/V_0 of inflow to mainstream velocity about 0·03. A characteristic feature of most area suction results is that the lift increment ΔC_L at constant incidence rises rapidly with V_s/V_0 until the flow is completely attached on the flap, but thereafter remains sensibly constant, in contrast with blowing. There is now a wide choice of porous materials satisfactory from aerodynamic, structural and non-clogging aspects. However, to ensure low flap-suction requirements, interference from flow breakaway in wing body junctions or from rough flow leaving the wing leading edge should be precluded by careful design. Theoretical treatment of the associated boundary layer development has proved difficult, since the boundary layer invariably becomes turbulent before reaching the suction area at the flap knee where it then negotiates severe adverse pressure gradients over the highly curved surface. As regards specially designed thick aerofoils, exploratory studies indicate that $C_{L\,max}$ values as high as 4 or 5 could be achieved with trailing edge flaps and moderate suction through multi-slots or a porous area. Such aerofoils should not be overlooked therefore for obtaining S.T.O.L. performance together with large storage capacity, provided high cruising speeds are not required.

Research on nose-suction applied to thin wings has been extensive, comprising two-dimensional experiments and theory on area suction and on specially designed slot-suction sections, as well as three-dimensional experiments with both area suction and slot suction on conventional sections. For wings 10 per cent thick or less without significant nose camber, the optimum extent of porous area lies within the first 3 per cent chord and the optimum location of a spanwise suction slot is forward of 2 per cent chord. For minimum power requirements, the resistance of the porous area should be graded chordwise to ensure that the inflow velocity does not increase unnecessarily towards the rear. The slot width should be as small as possible commensurate with choking considerations and more than one slot would often be profitable. On swept-back wings, more suction is usually required towards the tip, but it is usually beneficial to extend the suction well inboard, the spanwise extent being a compromise between the need for high $C_{L\,max}$ and high pitch-up C_L. Theoretical arguments for the avoidance of laminar separation with area suction suggests considerable favourable scale effect ($\propto R_c^{-\frac{1}{2}}$) on the suction quantity requirements. However, although such favourable effects have been found experimentally for area suction and slot suction, there is as yet no justification for extending this argument beyond about $R_c = 3 \times 10^6$. The experimental suction quantities required with a porous area ($C_Q \simeq 0{\cdot}001$) have been at least five times as large as theoretical estimates. Even so, they are far less than those required with a single slot, and the suction head for area suction need not be higher than for a slot provided the porous area is carefully graded or compartmented. Finally, the use of area suction at the knee of a leading edge flap instead of at the wing nose can further reduce the suction requirements, both in respect of quantity and pressure head.

6. Concluding Remarks

6.1. DIRECT JET-LIFT (TURBO-JET AND TURBO-FAN)

Most of the basic aerodynamic research has been carried out within the past three or four years and has been mainly concentrated on wing layouts. Forthcoming research will be directed towards body installations (fuselage and nacelle) to reduce mutual interference between the air flow through the lifting-engines and the

*Comparative full-scale tunnel and flight tests have been made in America by the N.A.S.A on area suction, both at the trailing edge flap knee and the wing nose.

external flow around adjacent aerodynamic surfaces, and to minimise structural penalties.

The experiments at *zero forward speed*, on low aspect ratio wings with centrally located jets (pure-jet and fan) have suggested some promising schemes for the alleviation of adverse ground effects, which arise unless there is a substantial central boss to provide an annular jet. However, the investigations need to be widened in scope, and to include fuselage and nacelle layouts; both stability and lifting efficiency are of considerable importance and the possibilities of favourable arrangements, as well as methods of alleviating unfavourable effects, must not be overlooked. Recirculation of hot gases back into the engine intake is extremely objectionable and deserves much more aerodynamic research than hitherto, towards a full understanding of the associated flow patterns and their control. Even out of ground effect, the particular layout of a multi-jet (or intake) system could have an important bearing on the lifting efficiency, stability, or tendency to recirculation, especially if rapid rates of descent are envisaged.

The effects of *forward speed* on the external aerodynamics have now been studied for several simple low aspect ratio wing installations without ground. It has become clear that the initial loss in lift occurring as speed is increased becomes smaller for the larger jet exit to wing area ratios appropriate to fan systems, as compared with pure turbo-jets. So it is important that the correct practical values be represented in model tests. In addition, multi-jets can profitably be mounted together in a spanwise row as far back as acceptable from other balance considerations (say half-chord).

Some favourable mutual interference effects from the wing-fan layout can therefore arise from performance aspects, but the possible accompanying stability and trim difficulties need to be watched. Even with a body installation such interference may still be present, since the nacelles or fuselage can have appreciable surface areas downstream (or upstream) of the jet exit (or suction intake), and the wing may in any case be close by. In tests on specific aircraft configurations, both longitudinal and lateral stability derivative measurements are essential, together with exploration of the flow (downwash and sidewash) at likely tailplane and foreplane locations. Again, since S.T.O.L. as well as V.T.O.L. operation is likely to be demanded, the effect of ground on performance and stability at forward speed must be studied.

Although a few investigations have been completed on *inlet and outlet vanes* for wing installations, much more detailed design and testing is needed to provide systems which are both efficient aerodynamically and acceptable in practice. The inlet probably presents the more difficult problem, particularly since the question of starting the lifting engine as well as providing a satisfactory inlet flow has to be resolved. Some further experiments are planned at the N.P.L. on a fan installed in a rectangular wing and in a fuselage. Investigations by the N.G.T.E. and engine firms are also desirable, in parallel with their work on acceptable inlet flow distributions from the standpoint of fan performance and possible blade vibration.

There is little theoretical guidance on the round jet emerging from a lifting surface in a mainstream and on the effect of proximity to the ground. Theoretical treatments taking mixing effects into account either by direct or semi-empirical approach would be most valuable, and could be suitably complemented by the appropriate fundamental experiments on jet paths and transverse profiles.

6.2. PROPELLER LIFT

Although little work on propeller lift systems has been carried out in this country, both tilt-wing and deflected slipstream research aircraft are now being flight tested abroad, following on extensive model tests. Nevertheless, further model experiments for the better understanding and prediction of the lateral and longitudinal stability derivatives are certainly needed. The R.A.E. experiments on a four-propeller tilt-wing deflected slipstream model, started early in 1959, helped to establish satisfactory model design and tunnel testing techniques for such models, provided guidance on the magnitude of the tunnel interference in the 11½ ft. × 8½ ft. tunnel, and explored the usefulness and adaptability of the 24 ft. tunnel equipment for general V.T.O.L./S.T.O.L. model testing. The exploratory longitudinal force measurements carried out for both the tilt-wing and deflected slipstream configurations were to have been followed up by six-component force measurements and flow studies under a wide variety of conditions. However, the experiments will now be limited to a brief examination of the lateral stability derivatives of the tilt-wing configuration for comparison with other V.T.O.L./S.T.O.L. systems.

6.3. JET FLAPS

The basic aerodynamic principles of jet-flap wings in steady motion are now reasonably well established, both without and with sideslip. Further interesting studies could arise from current project studies on mixed jet-flap and conventional round nozzle configurations, such as S.T.O.L. applications with the jet-flap mainly for high lift and the round jets mainly for thrust, or V.T.O.L. applications with the jet-flap incorporated to help lower the transition speed.

The extensive wind tunnel experiments of the past three years have ensured that reasonable estimates can be made of lateral stability derivatives as well as of lift, pitching moment, thrust, and downwash at the tail, at least with wings of moderate aspect ratio, sweep and jet deflection (full span). In particular, conventional estimates of rolling moments due to sideslip were found to be quite inaccurate, and the deficiency in thrust from the value for inviscid flow was shown to be appreciable at large flap angles. More experiments are certainly desirable, particularly to examine the effects of spanwise variation of jet angle in more detail. Tests have demonstrated that flow separation over the front of a jet-flap wing at high lift coefficients can be readily minimised with boundary layer control at the wing nose, either by blowing (or suction) or by shape design

thereby precluding stalling at low incidences and loss of thrust. However, there is scope for further fundamental research (experimental and theoretical) to provide methods of reducing and predicting the deficiency in thrust caused by high skin friction, violent mixing near the jet exit and slot internal losses. Experiments on the effects of ground proximity are still in progress at the R.A.E., not only in relation to lift and thrust, but also to longitudinal and lateral stability, which may well be the limiting factor on acceptable jet angle (or C_μ) near the ground. Some measurements of at least one damping derivative (probably n_r) under oscillatory conditions are then planned, to determine the adequacy of quasi-steady treatments for the derivation of dynamic stability derivatives out of ground effect. More generally, it is worth adding much of the experimental work on jet flaps has encouraged the development of new experimental techniques and better understanding of jet effects on mainstream flows about lifting surfaces; this has assisted substantially the researches on other powered lift systems.

The aerodynamic theories developed for jet-flap wings are still mainly restricted to the case of thin aerofoil sections and jets in inviscid flow, being comparable in accuracy to simple thin aerofoil and lifting-line theories for conventional wings. They have provided a valuable basis for the analysis and correlation of experimental results and for prediction. Unfortunately, however, the influence of viscosity and the existence of non-planar vortex sheets cannot always be ignored, particularly as regards thrust and downwash with large jet deflections, spanwise variation of jet angle or part-span blowing, so that semi-empirical treatments have still to be used to ensure satisfactory estimates. In addition, more representative and elaborate theoretical treatments are required on the effects of sideslip and proximity to ground. Often, satisfactory predictions can only be ensured by making semi-empirical estimates.

6.4. BOUNDARY LAYER CONTROL

During the past decade, boundary layer control by blowing or suction over trailing edge flaps and over the wing nose have been established as effective and practical methods for improving lifting efficiency. Although much of the research was originally aimed at providing acceptable landing and take-off of high-speed aircraft configurations, the experience could be applied for S.T.O.L. applications, either with boundary layer control used in its own right, or in conjunction with other schemes such as propeller lift and jet flaps. Blowing has usually proved more attractive and acceptable than suction with turbo-jet aircraft, provided the permissible compressor bleed is not marginal and the associated thrust losses are not objectionable. In other circumstances, however, area suction could be more profitable with its smaller pumping requirements; the choice will depend on the available pumping systems and installation problems.

The blowing and suction requirements for boundary layer control are now much less than were originally envisaged some years ago, while considerable experience has been acquired on the design of slots and porous surfaces. Reliable estimates can be made of the boundary layer control requirements and the associated lift and pitching moment increments, but the available methods for predicting the associated drag and downwash changes with part-span trailing edge flaps are still inadequate. Unfortunately, a systematic experimental investigation of aspect ratio, sweep and flap span effects is still lacking. Detailed studies of the influence of boundary layer control on lateral stability and control have also not been made.

A considerable amount of theoretical research has been reported on the maintenance of unseparated laminar flow under adverse pressure gradients by area and slot suction. The corresponding problem for turbulent boundary layers with blowing or suction has proved much less tractable, but warrants further study. As with jet-flaps, the effects of the non-planar vortex sheets arising with part-span flaps and large flap angles also needs theoretical investigation, particularly in relation to the prediction of drag and downwash changes.

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DISCUSSION

K. W. Clark (Ministry of Aviation, *Assoc. Fellow*): He welcomed the opportunity to congratulate his friend John Williams on a very illuminating insight into all the research work that was going on into this topical subject. He was intrigued by the courage of what was formerly the Helicopter Association in permitting discussion of a rival system. One could easily see what formidable competition would arise in the near future.

He had some questions on the applicability of some of the systems. It was clear that for prolonged hovering the helicopter could not be beaten, because it had a low disc loading. For high-speed V.T.O.L aircraft, in which it was important that any lift system should have a minimum of drag, a vertical jet system was, obviously, equally attractive. It might consume a lot of fuel but, on the other hand, it was used for such a short time that the weight of the fuel used was much less important than the drag of the lifting system itself.

Those two objects seemed to be fairly clear, but what was the author's opinion about the intervening ones, when used for vertical lift, for example deflected slipstream and tilted wings? These seemed to make such a fundamental alteration to the aircraft that they must penalise the normal cruising performance considerably. Was there a real future for these?

The Americans were investigating the fan lift for their aerial vehicles, the so-called "flying jeeps," for which it seemed quite promising. When considering fitting fans into an aircraft, however, there seemed to be such a lot of fans and so little aircraft left that one wondered where they were going. When thinking of an aircraft of about 50,000 lb., the fan area on the American basis would be prohibitive: but presumably, for an aircraft, it would be possible to have a more heavily loaded fan.

The fan areas used at the R.A.E. appeared to be rather small. The author had been heard to say that they had to make the wing large to get all the machinery into it. Possibly the same thing might apply to the full-scale. It might be difficult to fill much of the wing with fans and, at the same time, to want the wing for the purpose of putting in all the lifting machinery.

The question of short take-off was an easier one. Where the deflected slipstream and tilt-wing methods were used only to shorten the take-off, the aircraft would be closer to a conventional type and the cruising performance would be less penalised. The jet flap would seem to have a good potential in assisting heavily loaded jet aircraft; there might possibly be a great future for it in that respect.

Boundary layer control had already been fitted to the Lockheed Hercules as an afterthought to shorten the take-off. This seemed to be a useful application also. On the shortened take-offs, therefore, all these systems appeared to have a good application.

Regarding circulation of efflux vertical jets, which tended to reduce the wing lift and to push hot air into the intakes, some time factor must arise. On the S.C.1, the engines appeared to take quite a long time to run up and there was ample time for any circulation to build up. The engine manufacturers had given the assurance, however, that future engines would run more quickly so that the aircraft would lift off the ground almost as the throttle reached the far end of its travel. In that case, might the aircraft lift off before these adverse circulations had built up?

Dr. Williams: British research on propeller-lift systems was small compared with that completed in the U.S.A. He felt that such aircraft had a promising future since cruising speeds as high as 350 knots were now envisaged. There seemed to be a strong case for a six-propeller aeroplane, particularly with a view to meeting satisfactorily the safety requirements associated with engine cut, or shafting and blade failure. The deflected slipstream configuration seemed the most appropriate for a powered S.T.O.L. application. If V.T.O.L. were demanded, then a tilt-wing configuration with a small slotted flap seemed better. As with other powered lift systems, considerable research was essential to investigate the likely behaviour near the ground as well as through transition, particularly in order to be able to assess the degree of auto-stabilisation required.

Concerning Jeeps, existing test vehicles appeared to be under-powered, but this was possibly due to problems of installation and design in these early stages. It was difficult to assess what future such vehicles really had, particularly in their present forms using large rotors. Originally, shrouds were included to improve the vertical thrust, but these led to stability problems at forward speeds and so were replaced by simple guard-rings. With fan-wing aircraft applications, the disc loadings would tend to be much higher as Mr. Clark had said, so that the size (and weight) of the lifting units would become smaller relative to that of the whole vehicle. The prospect with integral fan engines might be even better from this aspect, although the permissible hover time would become smaller because of increased fuel consumption.

Naturally as regards S.T.O.L., he felt that jet flaps could be profitably employed, particularly with a mixed configuration where the jet flaps were used primarily for high lift and round jets mainly for thrust. Admittedly, such schemes might well be more attractive for take-off field lengths between 1,000 and 3,000 ft., rather than the more restricted standard of 500 ft. Certainly, more sums should be done with a view to clearing up the practical economics of jet flap operation for various runway lengths. For such calculations, adequate information on thrust as well as lift performance was clearly essential.

Many V.T.O.L./S.T.O.L. systems seemed quite attractive, but more information on ground effect was vital, not simply on the question of effects on lift but also on the effects in relation to stability and handling. Some aerodynamic research was now being done on jet-blowing models at the R.A.E. in this connection and the problems of installing a moving ground in a wind-tunnel were under consideration.

"Recirculation" was a term which had been used loosely to describe flow patterns which occurred with V.T.O.L. aircraft near the ground, leading to either suctions on the aircraft lower surface or the ingestion of the hot jet air into the engine intakes. These two phenomena were fundamentally different, since convection effects played a large part in the latter but tended to be of secondary importance in the former. There was little evidence on the rate at which such effects could build up after the jet efflux started or as the ground was approached, but presumably the patterns were established in a few seconds rather than minutes. Neither type of recirculation could automatically be ignored on account of time lag, although this aspect seemed worth further study particularly when the aircraft was moving.

I. Chichester-Miles (Blackburn Aircraft): He wished to make an observation about the way in which short take-off and vertical take-off systems should be used. In the

Aircraft Industry their business was to make *flying* machines but when they designed an aircraft as a really efficient flying machine it was rather difficult to get it off the ground. It was necessary, having optimised the design for the flight condition, to consider what was the best way of getting it out of what seemed to be a convenient space upon the ground.

Starting from this point of view, one began to see certain ways of doing this that matched the cruising aeroplane better than other ways. At the moment, for example, when engine weights were significant and their costs very significant, and when engine fuel consumption was relatively high, there was a case to be put forward for keeping a relatively high ratio of static thrust to cruising thrust. Thus, having made a flying machine with a certain cruising thrust requirement, when one tried to get it off vertically or in a very short distance, one could have a given system that suited both ends of the range.

From that viewpoint the tilt-wing was a very well matched machine. One could not help mentioning that it was a type which ought to be considered by the Rotorcraft Section of the Society, because when it was hovering it was in a way a tandem helicopter with a few appendages; wings, a tilting fuselage and so on.

To think first of all of the flight regime and secondly of the take-off and landing performance was a profitable way of discovering a useful V.T.O.L. or S.T.O.L. system. In this connection it was rather tragic that in Britain they had perhaps neglected those systems which had a very high ratio of static thrust to cruising thrust, such as the propeller lift systems.

The author had pointed out that vertical take-off aircraft could often be changed into short take-off aircraft by over-loading, in the same way as S.T.O.L. aircraft could be used at higher weights from long runways. It sometimes appeared, on paper at least (and it would be of interest to know whether the author's experiments supported this view) that changing a V.T.O.L. aircraft into a S.T.O.L. one was almost as difficult as changing a short take-off aircraft into a V.T.O.L. One could think out a configuration of vertical take-off aircraft in which the power requirements during transition were as high as those in hovering flight. This could occur both with such a thing as a high wing-loading tilt-wing V.T.O.L. or, with a low aspect ratio fan lift aircraft. If the critical power requirement occurred during the transition, when the aircraft was over-loaded and somebody said " now we will give it a bit of a runway to go along " it would be found impossible to get it up to a reasonable speed or to go through transition. That meant that if one's eye were kept on using V.T.O.L.s it would be necessary to start distorting the configuration to get the short take-off capability. It might therefore be worth bearing in mind that for some types of aircraft V.T.O.s were V.T.O.s in the same way as S.T.O.L.s were S.T.O.L.s and they were not readily interchangeable.

The Chairman (R. H. Whitby, Performance and Analysis Manager, B.E.A., *Fellow*): The suggestion that the tilt-wing design was better matched as between cruise and take-off power requirements, reminded him that two years ago the Helicopter Association was given a talk by Mr. W. Z. Stepniewski of Vertol,* who was working on such a design. His own recollection of that occasion was that the balance was not very good. In fact, it was necessary to assume that the aircraft was cruising at 20,000 ft. or more and at a quite low proportion of the available maximum continuous power.

If one accepted as a criterion that there should be a match between the take-off and the cruise power requirements, perhaps the helicopter was a better compromise in that respect. It was true that the general criticism of the helicopter had been its lack of cruising speed, or relatively low cruising speed. Developments were now being undertaken, however, which gave promise certainly of 150 knots or, perhaps, considerably more, up to about 200 knots.

Mr. Chichester-Miles: The kind of propeller-lift aircraft one was thinking about, whether it matched or not, perhaps depended on the disc loading and the cruising altitude. Studies which he had come across on relatively low disc loadings on propeller-lift aircraft cruising relatively fast and relatively high seemed to show the possibility of a much better match than the Chairman had indicated.

The fundamental fact was that when considering a high jet velocity system, if a propeller aircraft were badly matched and if the lifting system were used for cruising, a higher jet velocity lifting system would be even worse matched than a propeller one. This was what tended to make people think in terms of separate lifting engines. Jet lift systems simply could not be matched properly at all. From that point of view, therefore, although it was probably not easy to match any of them, the lower the disc loading at the present stage, the easier it would be.

Perhaps one of the reasons for the slow progress of the helicopter was the fact that it was originally designed to amaze people by its field performance, which was a zero field performance. It was not designed fundamentally as a forward-flying machine. This, philosophically, might be the reason why it had not made as great strides as it should have done.

Dr. Williams: He felt that there was a strong case for propeller-lift aircraft, either for V.T.O.L. or S.T.O.L. applications, if cruising speeds between 150 and 350 knots were needed. For aircraft designs with higher cruising speeds, Mr. Chichester-Miles' arguments were hardly applicable, and turbo-fan engines for both propulsion and lift seemed much more appropriate. He agreed with Mr. Chichester-Miles that S.T.O.L. operation of over-loaded V.T.O.L aircraft was not necessarily straightforward since significant aerodynamic interference could arise from proximity to the ground at forward speeds, in addition to the transition problems already mentioned.

He would like to promote some discussion on the likely method of operation of so-called V.T.O.L. aircraft from airfields. At present, he understood that helicopter take-off and approach paths were inclined at about 10° to the horizontal, not vertical at all! Would similar operation be required with the newer type of V.T.O.L. aircraft in practice, particularly since large vertical thrust margins could not always be guaranteed?

The Chairman (R. H. Whitby): What helicopters were at present doing, *i.e.* the one-engine machine, was no indication of what they were capable of doing given two engines with an adequate power margin. In these circumstances, they could become much more nearly vertical take-off aircraft. Also, given adequate stability, they could approach at low speeds and at much steeper angles. Therefore, one's views should not be too much coloured by the behaviour of the existing relatively under-powered helicopter with one engine. As helicopters had become

*Tilt Wing Aircraft in Comparison with other V.T.O.L. and S.T.O.L. Systems. W. Z. Stepniewski. *Journal of the Helicopter Association of Great Britain*, Vol. II, No. 6, Dec. 1957.

more practical as pieces of ironmongery and the intention to use them in bad weather conditions had become more firm, the question of operating in these circumstances had become most important. He did not know very much about the work which had been going on in relation to other V.T.O.L. aircraft, but he was left with the impression that for them to operate in poor weather rather complex auto-stabilisation systems must be incorporated.

Dr. Williams: Two years ago, his impression was that British engineers considered full auto-stabilisation to be desirable for V.T.O.L. aircraft operation, while the Americans seemed to be striving for purely manual control. Now, it seemed that the two sides had come together. It was well established that some V.T.O.L. machines could be flown manually by an experienced pilot on a calm day, but for more general operation, some degree of auto-stabilisation seemed unavoidable. Undoubtedly, one of the most interesting future developments could be the incorporation of an automatic blind-landing system in conjunction with the auto-stabilisation equipment.

K. W. Clark (Ministry of Aviation, *Fellow*): He would like to hazard a guess that all these V.S.T.O.L. aircraft, including helicopters, would have auto-stabilisation fitted if they were to operate completely blind at night. Unless this was done, the operating value of the aircraft would be too limited. As regards helicopters being under-powered, this was no doubt due to operating them with a minimum amount of power for economy, and this trend was not confined to helicopters.

One could see vertical take-off aircraft not rising straight up in the air, but as soon as they were off the ground, they would be moving forwards. This would reduce the time the vertical lifting system was in use and cut down the transition time.

Mr. Chichester-Miles' point about equating take-off thrust with deflected slipstream aircraft might not apply to transports with vertical lifting engines and separate propulsion engines. Here one would switch off the lifting engines as soon as the machine was up. The propulsion engines would be equated to the necessary propulsive power required for cruise. On a transport aircraft great manoeuvrability was not required and one might cut down the available cruise thrust enough to give, say, about 3*g*. At the same time, one would cut down wing area to the amount required for cruise as well, and possibly dispense with flaps, so that there would be a saving on the amount of weight expended in carrying lifting engines that were not used in flight; it would not all be a dead loss.

For a military fighter, the situation was different. One might be expected to use a 6*g* turn close to the ground and there might be a need for all the power that could be obtained. There might then be advantages in combining the lift and propulsion engines, giving plenty of power in hand, although limiting the range a little in consequence.

E. Pribram (Fairey Aviation Co. Ltd., *Assoc. Fellow*): It appeared to him that the title of this lecture was, as Sir Winston Churchill would describe it, a " terminological inexactitude." The only examples he could think of where lift was not generated through the application of power were the balloon and possibly the sailplane.

While all lift thus required power, the amount needed to generate the same lift varied enormously. Although that was obviously not the only important criterion, he felt it merited at least passing notice. Dr. Williams, being interested only in the aerodynamic aspects, had not mentioned it.

In a helicopter, a fuel flow of one pound per hour generated 20-25 lb. of lift; vertical jet lift gave only about one pound of lift for the same amount of fuel.

Arranging the vertical lift systems considered according to this criterion, the helicopter came on top and the vertical jet at the bottom, with the ducted fan next to it.

Where did the tilt-wing machine stand? In the published reports no information on this was to be found. Personally, he thought that due to structural difficulties of large diameter propellers and the problem of clearance, it would come out pretty badly and therefore he had never believed in this type of vertical lift aircraft. Perhaps the lecturer could throw some light on this question.

Turning now to the so-called S.T.O.L. lift systems, the jet flap as a lift generating mechanism was a poor performer; but it would not be fair to look at it in this way. Here one obtained lift as a by-product of thrust, and it then became an efficient way of creating lift.

Regarding boundary layer control, this could be achieved, as Dr. Williams had pointed out, by blowing or by suction. There was, according to American reports, a four-to-one difference in favour of suction in the amount of energy required to suppress flow separation. This statement, he felt, needed qualification. The blowing power, expressed by the moment coefficient C_μ varied by as much as 100 per cent between different tests. From tests they had done he concluded that apart from the geometry of the aerofoil and flap, the shape of the slot and its relative width appeared to be important parameters.

He had, however, seen one American report which gave a C_μ figure of one-tenth of the usual amount, *i.e.* 0·003 instead of 0·03. This, if true, which he did not believe, put an entirely different complexion on the matter. Would Dr. Williams comment on this?

Dr. Williams: He agreed that the term " powered lift " was in some ways objectionable, but it was in common usage, at least in America. Under this convenient heading, improvements by boundary layer control (B.L.C.) to the aerodynamics of classical lifting wings and rotors could be included, as well as some recent developments on lifting systems for V.T.O.L. and S.T.O.L.

With such systems, the jet (or developed slipstream) velocity was of major significance, not only as regards the amount of power required for lift and the associated fuel consumption, but also in relation to noise, ground erosion and the size of lifting units. The propeller-lift aircraft (tilt-wing/deflected slipstream) had a jet velocity of about 200 ft./sec. compared with about 80 ft./sec. for the helicopter and more than 300 ft./sec. for ducted fan aircraft; this located propeller-lift in the spectrum. Propellers as large as 20 ft. in diameter had been considered, ranging from blades designed conventionally to lightweight versions following helicopter rotor techniques. In view of the successful development and operation of propeller-lift research aircraft in the U.S.A., Mr. Pribram's pessimistic attitude to this type of aircraft seemed unjustified. The safety aspects relating to failure of an engine or part of a lifting unit had been carefully considered and the practical solutions devised were quite realistic and promising.

As regards boundary layer control, the choice between blowing or suction for a particular application was quite clearly dependent not only on their relative aerodynamic efficiency and structural simplicitly, but also on the type of power supply best suited for the aircraft. Slot blowing requirements had been much reduced over the past few years by careful attention to slot design and flap geometry. Area suction was still a rather more sophisticated and

economic system, but was far more sensitive to flow disturbances from wing body junctions, leading edge discontinuities, and so on. Again, provided the B.L.C. quantities available were not marginal, appreciable lift gains were possible with blowing beyond conditions for flow attachment. Nevertheless when starting with a new aircraft design, suction as well as blowing was well worth consideration.

The C_μ values quoted in various reports often referred to quite different flow or lift conditions as well as to different wing geometries. The requirement for fully attached flow over flaps at 60° flap angle was more like 0·03 rather than one-tenth this figure, although there might be some reduction at very low aspect ratios.

A. C. Clinton (Bristol Siddeley Engines, *Fellow*): The vertical take-off and short take-off work that was being done was inspiring. If only some of this inspirational work had been put into helicopters in 1920 when there was complete readiness to give money for an old German invention, everything might have been going very well.

On the engine side, it was possible to have all the brute force one wanted. For working in forward areas which could be reached by flying from base, a combat vertical take-off aircraft must be able to go like a rocket to get out of the way. The whole mobility of the modern Army was much greater and more freedom was required. If the vertical take-off combat machine did not possess these qualities, it was not likely to be successful in meeting the demands that would be made of it. It must not stay in one place too long.

He hoped that the work that the author was doing would soon be converted to ironmongery and that he would not be stopped by some of the scientific people who so frequently pessimistically turned things down.

M. L. Hayward (de Havilland Aircraft Co., *Graduate*): The aerodynamics so far discussed had been on wings themselves. Were any tests being made on the forces on the ground? What he had in mind was ground erosion and pressure distribution on the ground.

Dr. Williams: Some investigations of the effects of jet dynamic pressure and temperature on the erosion of various types of ground surface had been made both in Great Britain and the U.S.A. There was, of course, the interesting case of the Short S.C.1 aircraft landing vertically on a football pitch, with only slight scorching of the grass. Hot model tests and the interpretation of such results for application to full-scale were not straightforward. However, more research was certainly needed on pressure and temperature distributions over the ground for various jet-lift aircraft configurations.

E. G. D. Kemp (de Havilland Aircraft Co., *Graduate*): The work done by the author and Mr. Gregory of N.P.L., had shown that for a lifting fan installed in the centre of a wing, there was a considerable loss of lift and also an undesirable pitching moment near the ground. In fact, from this point of view it would be difficult to put the fan in a worse place.

Had the author done any work on wing-tip mounted fans, or with fans mounted in such a way that one could move towards the hovercraft principle and gain something in lift near the ground, instead of losing so much? Although the author had shown that channels placed under the aircraft would help, these might not be practical for military operation in forward areas.

Wing-tip mounted fans had been used successfully in the Doak 16 and it had recently been announced that the V.T.O.L. Mach 3 fighter to be built by Messerschmitt and Heinkel had two rotatable engines mounted on each wing tip, in addition to two engines in the fuselage purely for lift.

Mr. Clark had mentioned that the results of a few aircraft sums showed that the ratio of fan area to wing area required was much larger than the author had tested, although his area ratio would be about right for turbo-jet supported aircraft. Could the author say what effect jet efflux velocity had on the aerodynamic characteristics which he had measured? Could the results which he had obtained with relatively low fan disc loadings be applied to turbo-jet supported aircraft?

Dr. Williams: He accepted that, from static lift considerations near the ground, the central jet or fan location seemed about the worst possible. However, consideration of wing jet and fan installations had begun several years ago and it was not known then whether losses would be serious or not. The static test programme discussed in his paper was in the nature of basic research on aerodynamic problems associated with such installations and on the effects of various parameters, such as the ratio of jet-exit area to wing-plan form area (or equivalent diameter ratio). The jet Reynolds number (or disc loading parameter) seemed of secondary importance. Quite large as well as small diameter ratios had now been studied and, with the central hub present, favourable lift effects had been found in Mr. Gregory's wing-fan tests. The written version of the paper stressed that peripheral or other jet arrangements giving favourable ground effects, for example by forming an air cushion as with the Hovercraft, needed to be explored. But it must be remembered that with vehicles intended purely for operation near the ground, clearance might be only a few per cent of the vehicle diameter, while with jet or fan lift aircraft the minimum ground clearance was probably of the order of 10 to 30 per cent.

Unfortunately, the aerodynamics became even more involved at forward speeds and the choice of jet location and arrangement was still of considerable importance. Both at forward speed and under static conditions, the problem was not merely one of getting the lift right; matters such as trim, stabilisation and control throughout the wide speed range had to be studied. In this respect, the mounting of tilting lifting engines or ducted fans at the wing tips well away from the aircraft c.g. could be particularly troublesome in the event of an engine or fan failure. Inevitably there must be some design compromise between the desirability of having most of the lifting units close to the aircraft c.g., yet far removed from the wing body or ground to avoid interference effects; in addition, the advantages of low velocity jets for hovering must be balanced by the requirements of high cruising speeds.

J. S. Shapiro (Consulting Engineer; *Assoc. Fellow*): He wondered whether the phrase "powered lift" was not merely bad linguistically, but also bad logically. He was an unashamed helicopter rotary wing enthusiast, and when listening to the lecturer the main thought which occurred to him was of the extraordinary things that people would do to avoid rotary wings. That was the only thing that united the author's four classifications of direct jet lift, propeller lift, jet flaps and boundary layer control. Nevertheless, there was a logical connection between the last three, but no connection with the first.

A more appropriate phrase would be "assisted (or artificial) circulation," which made sense. There was something in common between the last three classifications, but the direct jet lift was completely different. When it

operated, the wing was a nuisance. When it did not operate, it was simply carried around. The last three had something to do with creating a circulation which the aerofoil did not have by being dragged through the air.

Perhaps an answer could be given in a rule of thumb manner to a problem concerning rotary wings. A given propeller with given disc and power loading could give a certain lift. Was it possible by any combination of the propeller with aerofoils, say by deflecting the jet, to increase this lift? Was there a generalised way of looking at it that would give some kind of ideal that might be achieved?

Dr. Williams: Although he too did not particularly favour the term "powered lift," he had used it in his title because of its brevity and convenience. He might have simply specified "V.T.O.L.-S.T.O.L." but, as he had already mentioned, he had not wanted to exclude applications for ensuring acceptable take-off and landing performance from moderate runways. The four categories of systems discussed in the lecture represented some areas on which R.A.E. and N.P.L. teams had recently been carrying out aerodynamic research. The written version of the paper pointed out that other systems were of interest and mentioned particularly that further work seemed desirable on the improvement of lifting rotor and helicopter performance.

As regards the logical connections between the four categories of the paper, jet flaps and boundary layer control were naturally associated together in that they were essentially intended as methods of circulation control about a lifting surface at forward speeds. Direct jet lift and propeller lift, on the other hand, were primarily envisaged as methods of generating lift roughly equal to the deflected thrust of the propulsion units, at least under static conditions. However, at forward speeds, inclination of either the jet efflux or propeller slipstream to the mainstream flow direction could lead to lift magnification in a manner akin to jet-flap effect.

In view of the special helicopter interests of the audience, he wondered whether Mr. Shapiro or others saw a practical future for boundary layer control and jet flaps as methods of improving lifting rotor performance. No doubt such methods might usefully accompany other schemes for improving the helicopter in both hovering and forward flight. From reports of Monsieur Dorand's recent lecture, it seemed that the aerodynamic principle of jet flaps could be applied to lifting rotors, despite the centrifugal effects on the flow and that practical application might be profitable. Unfortunately, he had not yet been able to study Monsieur Dorand's written paper in detail; he would welcome Mr. Shapiro's opinions not only on both these points but also as to whether further research work could be justified.

Mr. Shapiro: In this matter he must bow to the superior knowledge of Monsieur Dorand, who, in his lecture in November 1959,* gave a full report of what had been happening and the confident prediction that it was both possible and promising and that the foundations had, in fact, been established. Beyond this, he had only heard through a back door that similar claims had been made in German tests.

Therefore, in view of, mainly, the very fully reported results of Monsieur Dorand, the answer was definitely in the affirmative. Certainly, from the aerodynamicist's viewpoint, there was a very promising means for reaching the kind of speeds mentioned by the Chairman of 200 and even 250 m.p.h. at very acceptable efficiency.

Captain E. C. Beard (Ministry of Aviation, *Assoc. Fellow*): He had been fortunate during the past year to have seen at first hand the majority of the American work in the field under discussion. He was now engaged in developing current helicopter work and, in his opinion, as an earlier speaker had said, if the same amount of research had been devoted to improving the basic helicopter from its earliest, almost toylike, stage as had been applied to vertical take-off as described by the author, its progress would have been much farther advanced.

At the present time rotor efficiencies were much too low and must be improved. If this were achieved, one would not see very much future in the more sophisticated vertical take-off machines while they still kept in the middle speed ranges.

As a naval officer, he had for many years been engaged, as somebody once described it in an examination, "in trapping aircraft when they got back to the deck and flinging them into the sky." In other words, short take-off was a problem which had always been present. How everything was to be brought together to provide an efficient fighting machine, which could be operated from a ship which had finite length, at the same time taking up all the advantages that were afforded by high speed, was one of the very big question marks which could not be answered.

He wished the author fortune in the new work which the lecturer had been given to do in the helicopter field, largely at his instigation. He felt sure that some of the applications of jet flap and boundary layer control could be brought to bear on the rotor system with advantage.

D. M. Jameson (Air Registration Board, *Assoc. Fellow*): Speaking personally, what impressed him was the extent to which the airworthiness viewpoint was being considered by designers even at this stage. From his point of view, the variety of possible design solutions meant that, at present, the investigation of future airworthiness requirements in this field had to be directed at specific problems rather than at specific types of aircraft; one of these problems—it might sound rather academic, but it was likely to cause difficulty—was in deciding where an ordinary aeroplane stopped and the unconventional, powered lift, aircraft began; the expression "S.T.O.L." seemed to be too vague for use in airworthiness.

There were some problems, for example reliance on automatic devices to provide stability, the solution of which might ultimately be of benefit to fixed-wing aircraft also. In this connection, one particular problem which had been mentioned was of interest to the A.R.B. It had been acceptable airworthiness-wise to have helicopters without automatic pilots, at least for flight under visual conditions. For many other forms of powered lift aircraft, however, auto-stabilisation appeared to be essential; what was the dividing line?

That might give a brief idea of the difficulties ahead.

*The Application of the Jet Flap to Helicopter Rotor Control. R. Dorand. *Journal of the Helicopter Association of Great Britain*, Vol. 13, No. 6, December 1959.

TECHNICAL NOTES

A Simplified Presentation of Shock Wave Parameters in Dissociating Air Flow

by

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AS IS WELL KNOWN, the analysis of shock waves is complicated when the gas becomes dissociated on passage through the wave. As well as showing a dependence on the Mach number of the incident flow and non-dimensional quantities characteristic of the nature of the gas, as does the analysis when applied to a perfect gas, it then also shows a dependence on the thermodynamic state of the upstream air, as described for instance by its temperature and pressure. A growing number of calculations is becoming available, especially for air in complete thermal and chemical equilibrium, but the interpolation to give results appropriate to the three independent variables (of upstream state and incident velocity) needed in any particular application can often be rather troublesome, and one has still less faith in extrapolation.

NOTATION

T_2 temperature downstream of shock wave
T_D characteristic temperature for dissociation
u_1 upstream velocity component perpendicular to shock wave
ρ_1 air density upstream of shock wave
ρ_2 air density downstream of shock wave
ρ_{sl} sea level air density

It is of interest therefore to note that the two particular combinations of variables appearing as the ordinates in Figs. 1 and 2, will usually be found to be primarily a function of incident velocity, and to vary only a little with the two independent variables of upstream state. This is illustrated in the figures by plotting the extensive data tabulated in Ref. 1, which refer to shock waves formed in atmospheric argon-free air having temperatures and pressures appropriate to various altitudes (as shown by the key to the point-symbols). These results are certainly not the only ones demonstrating this powerful method of collapsing the data, nor do they provide the most striking illustration which could be cited; but they do cover an unusually wide range, not only of speed, but also of upstream density—from about 0·3 to $0{\cdot}3\times10^{-5}$ of the sea level value. Data from other sources, covering values of upstream temperature from 150°K to 500°K, confirm that this independent variable has by itself only a small effect upon results plotted in this way.

The value of T_D is arbitrary in so far as it can be adjusted to improve the collapse of the data of Fig. 1, showing downstream temperature; in making this figure a value of $T_D=150{,}000$°K has been used. This value is immaterial to the collapse of the data of Fig. 2, which is seen to indicate a closely linear dependence of the quantities plotted; however, the approximating straight line is seen to intersect the ordinate at a value of 0·5 with this particular value of T_D.

It is possible to suggest the reason for this particular intersection and the linear dependence and, as well, for the

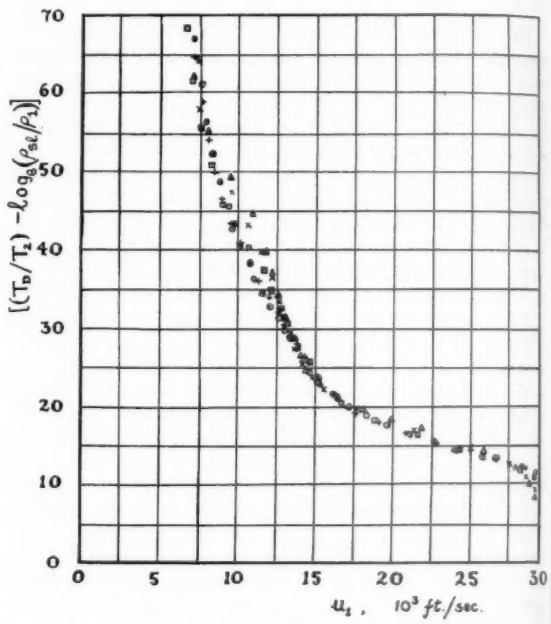

FIGURE 1.

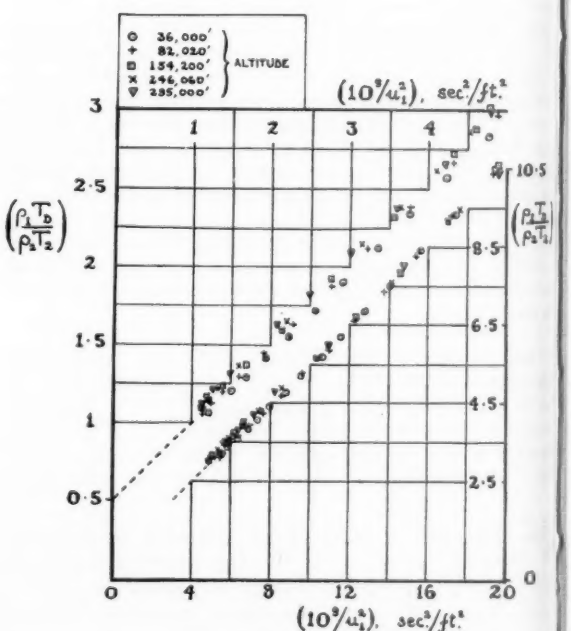

FIGURE 2.

Received 9th March 1960

apparently fortuitous nature of the collapse of the data of Fig. 1. For if the air behaved as the "ideal" dissociating diatomic gas of Ref. 2 and its pressure were low enough that the value of (T_2/T_D) corresponding to complete dissociation could be ignored compared with unity, then it may be shown that the data should indeed fall on a single curve in Fig. 1, and in Fig. 2 onto the straight line given by the equation

$$\frac{\rho_1 T_D}{\rho_2 T_2} = \frac{G T_D}{u_1^2} + \frac{1}{2}$$

where G is the gas constant of the diatomic species. In fact, the slope of approximating straight line of Fig. 2 would suggest a value of G in this formula appropriate to a gas of molecular weight 26·9 (as compared with 28·9 for air). The same theory would also indicate that the degree of dissociation is approximately $(u_1^2/2GT_D)$, or $(u_1^2/10^9)$ ft.^{2}/sec.^{2}, in our illustration. The success of the present method is therefore merely a reflection of the strength of the approximations of this theory. However, it ought to be pointed out that the shape of an approximating curve to the data of Fig. 1 bears no resemblance at all to the theoretical one derived for the ideal gas of Ref. 2, and the values of T_D quoted therein for oxygen and nitrogen (namely 59,000°K and 113,300°K respectively) are not reconcilable with the value which we find to give the best fit for air.

It will be appreciated that the data quoted can be applied not only for normal shock waves but also for oblique waves as well. The momentum and continuity equations could, of course, be used to give downstream pressure and velocity. However, it must be remembered that thermal relaxation and reaction rate phenomena may restrict the practical utility of the results.

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Stress Distribution Around a Central Crack in a Plate Loaded in Tension; Effect of Finite Width of Plate

Comment by R. K. PENNY
(*English Electric Co. Ltd., Whetstone*)

THE REAL OBJECT of Mr. J. R. Dixon's paper (page 141, March 1960 Journal) is difficult to determine. First he says it is to investigate the effects of *crack* length to plate width ratios on the stress distribution. He then says that this is not possible photoelastically, but proceeds to measure stress concentrations at the ends of *slots* bounded by circular holes. These are compared with a theory for *elliptical* holes.

As one method of reducing stress concentrations at the head of a crack is to drill a hole there, it is unlikely that the stress distribution in the model bears any relation to that in the fatigue specimen it is supposed to simulate. Further, is the theoretical problem of a cracked plate simply a study in elasticity?

However, later in his paper Mr. Dixon says that he is interested in ratios of stress concentration factors, namely K_m/K_∞ and K/K_∞. Are we to assume then that in this way the unknown crack root radius and effects of possible plastic regions ahead of the crack are eliminated? If so, would it not have been profitable to have verified the radius effect by drilling different size holes at the ends of slots for a given method of loading? Lack of verification of Mr. Dixon's thesis by such tests would surely necessitate the removal of the word "crack" from the paper.

Advice from Mr. Dixon as to whether he believes his results are applicable to different size plates (width, length, thickness), and to different materials, would be welcomed.

The result for K_m/K_∞ could have been obtained directly from Coker's work merely by putting $d=0$ in equation (3).

Received 4th April 1960.

MR. DIXON'S REPLY

VERY little is known quantitatively about the stress distribution in the elastic-plastic stress field around a crack, and at present many theoretical calculations are based on elastic solutions which exist for plates of infinite width.

The elastic-stress distribution around a central crack in a plate loaded in tension is a function of crack geometry, the nominal stress across the gross or net section of the plate and crack-length/plate-width ratio. A full discussion of the problem of finite plate width in relation to the propagation of fatigue cracks is given by Frost and Dugdale[1].

The present paper covers an investigation of elastic-stress distributions around slots and cracks by photoelastic and theoretical methods. The results are strictly only applicable within the linear stress-strain range of the prototype material and will not apply directly to the elastic-plastic region near the head of a real crack. They will, however, indicate the effect of the finite plate width in the stress field to which an actual crack is subjected.

In a plate of infinite width

$$\sigma_0 = K_\infty \sigma_g;$$

in a plate of finite width

$$\sigma = K\sigma_g = K_\infty \sigma_0;$$

therefore

$$\sigma_0 = K/K_\infty \sigma_g;$$

Received 27th May 1960.

where K_∞ is the known elastic-stress concentration factor at the head of the crack for a plate of infinite width, K the elastic stress concentration factor at the head of a crack in a plate of finite width and, in general, is not known, σ the maximum stress at head of crack, σ_g the nominal stress across gross section of plate and σ_0 the equivalent nominal stress for a plate of infinite width. The values of K/K_∞ given in the paper may be used as a correction factor applied to σ_g to obtain the equivalent nominal stress σ_0 for a plate of infinite width.

Inglis[2] has shown that certain holes in plates of infinite width may be replaced by an equivalent ellipse and that the elastic stress concentration factor (K) is given by

$$K = 1 + 2\sqrt{\frac{l}{\rho}};$$

where $2l$ and ρ are the length of the major axis and radius at end of major axis respectively of the equivalent ellipse. It was shown (Dixon[3]) using photoelastic methods that the stress distribution around a central narrow slot with a small hole drilled at each end agreed well with the theoretical solution for an ellipse of major axis equal to the slot length and having the same radius of curvature at the ends of its major axis as the radius of the drilled holes at the ends of the slot. The effect of drilling holes of different diameters at the ends of cracks has been investigated by Dixon[4] and the results also show agreement with the theory for elliptical holes. It was, therefore, a justifiable experimental approach to derive K/K_∞ by obtaining K from a photoelastic model containing a central slot bounded by circular holes, and K_∞ from a theory of equivalent ellipses.

It can also be shown theoretically from equation (3) that the difference in K/K_∞ for $d/l=0$ (crack) compared with the small but finite values of $\frac{d}{l} = \sqrt{\frac{\rho}{l}}$ for the slot in the photoelastic tests is negligible.

The values of K/K_∞ and K_m/K_∞ are applicable to plates of different thickness, width and length, providing that the plate-length/plate-width ratio is large enough for the stress distribution around the crack not to be seriously affected by the plate edge loading conditions. The results are also independent of the prototype material, but will only apply within the elastic range of the material.

The theoretical results for K_m/K_∞ should follow from equation (3) after summation of the infinite series. The solution given in the Appendix is more direct.

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THE LOW SPEED APPROACH AND CATAPULT LAUNCH PROBLEMS IN HIGH PERFORMANCE NAVAL AIRCRAFT—A CORRECTION

by

LT. CDR. D. J. WHITEHEAD, A.F.C., A.R.Ae.S., R.N.

(Chief Test Pilot, Blackburn Aircraft Limited)

Lt. Cdr. Whitehead's paper was published in the April 1960 JOURNAL (page 183) but unfortunately errors in the direction of the thrust vector arrows in Fig. 30 (page 194, April 1960) were overlooked.

The figure was queried by H. T. Edgecombe, A.F.R.Ae.S., and Fig. A is a corrected version.

FIGURE A. Vertical component of thrust at high aircraft incidence.

The third extant Branch is MANCHESTER, as I.Ae.E. in 1925 and R.Ae.S. in 1927.

THE CHARTER of the Institute of Aeronautical Engineers was granted to the Manchester Branch on 10th December 1925. The Minute Book records the Inaugural Meeting of the Branch on 21st January 1927. Reconstituted at a Meeting held on 7th February 1930 at the Grand Hotel, Manchester, and attended by Captain J. Laurence Pritchard, it then became the Manchester Branch of the Royal Aeronautical Society. The first Chairman was Mr. R. H. Dobson (now Sir Roy) and the Secretary was Mr. Frank Paxton in succession to Mr. Dennison Scarlett, who had been Secretary of the I.Ae.E. from the beginning. Several of those forming that Committee are still actively associated with the Branch to this day, notably Mr. C. E. Fielding, Chairman in the post-war years, and Sir Roy Dobson, who has been President for a number of years. From the early days up to the time of his death, Roy Chadwick was always interested in the Branch and enthusiastic for its progress and development.

Membership of the Branch was at first recruited from A. V. Roe and Company and later augmented from the Fairey Aviation Company. In the first year of its new existence the Branch held six lectures, arranged a number of successful visits to works and formed a library.

The Branch, caught up in the new national interest and enthusiasm for gliding, formed a Gliding Section in March 1930, and a primary glider was built by members at the Newton Heath works of A. V. Roe and Co. Limited. A Model Section was formed in 1932, by which time membership had grown to 150, nearly half from outside the Industry. In 1933 the construction of another two-seater glider was completed and for two years it was flown with great success at Woodford Aerodrome until 1935, when the Gliding Section removed to its own Headquarters at Great Hucklow and, by affiliation with several other Groups, became the Derbyshire and Lancashire Gliding Club, then as now, one of the leading Clubs in the United Kingdom.

Mr. J. A. E. Waterfall became the Secretary of the Branch in 1934, and has remained in that office to this day.

Up to the beginning of the war the activities of the Branch were well maintained with a full programme of lectures and visits in each year. With the outbreak of war, however, all activity was suspended until 1946 when, with a very much increased membership and plenty of new enthusiasm, the Branch came to life again. Unfortunately it suffered a great loss with the death of Mr. Roy Chadwick, its Chairman, in a flying accident in 1947. Mr. C. E. Fielding then became Chairman and held that position up to the last Annual General Meeting when he was elected President. Mr. J. R. Ewans is the new Chairman; Mr. B. A. G. Meads continues as Vice-Chairman.

At the Annual General Meeting held in May 1948 a very encouraging report was given of the revival of the Gliding Club which had then reached such proportions that it was agreed to separate it from the Branch and run it as an independent concern. In 1952 the Lancashire Aero Club decided to discontinue their affiliation and the Branch was faced with a consequent loss of 120 members. One of the proposals put forward to encourage the entry of new members was the formation of a Junior Section with a suitable programme of lectures and visits. This proved a successful venture under the guidance of Mr. A. Stewart and Mr. H. Lomas of Avro's. Total Branch Membership, including Main Society Members, is now about 340.

Lecture programmes over the years have reflected the technical development of aircraft, the problems raised by ever-increasing speed and complexity providing lecture subjects of fascinating interest, beyond all earlier conceptions of what might prove possible. This process is continuing, and over the years a high standard of lectures has been maintained, with a balance, as far as possible, between specialist subjects and those of general interest.

Since 1956 the highlight of the lecture programme each season has been the Chadwick Memorial Lecture, the first of which was given by Mr. H. Rogerson on the life and work of Roy Chadwick, who for so many years was Avro Chief Designer.

The Reynolds Hall of the Manchester College of Science and Technology is used for lectures.

The Branch has been well served over many years by members who have devoted a great deal of time and attention to its affairs. Since there is no reason to suppose that new members will not carry on with the same degree of enthusiasm the Branch can expect many more years of vigorous life ahead.

Hatfield Branch

The Second Halford Lecture was given on 11th May 1960 by Mr. J. S. Alford, of the General Electric Company, U.S.A. who had come especially to Hatfield to deliver his paper on "Power Plants for Supersonic Transports." About 350 members and visitors were at the Main Hall of the Hatfield Technical College to hear him.

The Branch Chairman, Mr. C. G. Long, welcomed the many visitors and then asked Dr. E. S. Moult, Technical Director of the de Havilland Engine Co. Ltd. and President of the Society, to take the Chair.

Dr. Moult first paid a tribute to Major Frank Halford, who had contributed so much to the design of aero-engines and recalled the First Halford lecture given last year by Mr. J. L. P. Brodie, who had died a few weeks later; he said the Halford lectures would always recall the memory of both Major Halford and Mr. Brodie.

Dr. Moult then introduced the lecturer as an old friend and colleague. He said that when the first Whittle engine was sent to U.S.A. in 1945, Mr. Alford of General Electric was the engineer who was asked to look at this novel method of propulsion. Ever since that he had been intimately connected with the design of jet engines many of which were well known on both sides of the Atlantic.

After expressing his thanks at being so honoured as to be asked to deliver the Second Halford Lecture Mr. Alford went on to analyse air-breathing propulsion operating experience with supersonic aircraft. He stated that approximately 90 per cent of all $M=2{\cdot}0$ flying had been done in aircraft powered by the J79 variable stator engine, and he gave a description of those features important for supersonic flight. An examination was then made of inlet duct—engine air flow match over the flight envelope. He went on to survey the operating flexibility of the variable stator engine in regard to meeting requirements for adequate stall margin for inlet duct—engine compatibility at both low and high corrected engine speeds. An evaluation was then made of airplane performance improvement resulting from use of the variable-geometry converging-diverging jet nozzle and the development of the propulsion system for the supersonic B-58 Hustler was described to illustrate the rewards of close and cordial technical co-operation between airframe and engine builders. The future prospects were examined with particular reference to fan engine configurations which appear promising for supersonic transports in the speed range of $M=2{\cdot}2$-$3{\cdot}0$. This discussion included supersonic cruise, take-off performance, acceleration capability, loiter performance, and engine component requirements. (The Lecture is to be published in THE JOURNAL.—*Ed.*)

Cambridge Branch

Mr. C. F. C. Sneesby, A.F.R.Ae.S., formerly Chief Designer of Marshalls' Flying School Ltd., and Chairman since its inception, of the Cambridge Branch, has resigned on taking up an appointment with Bristol Aerojet Ltd.

Mr. Sneesby was largely instrumental in the formation of the Branch, and his unstinting work and wise counsel will be greatly missed. The Committee and members wish him every success in his new venture.—GW-W.

Graduates' and Students' Section

Company Views on Recruitment—Part Two

The first part of this article appeared in the June JOURNAL. *Here the second half continues with the question of "Apprenticeship v. Direct Entry."*

There was some difference of view on whether university graduates without practical training should enter company departments directly or should take a post-graduate apprenticeship. One company favours direct entry, but more favour graduate apprenticeship. Another says that direct-entry people "will always lack two things, the advantage of knowing how the man on the shopfloor thinks and reacts, and the practical know-how for which there can be no substitute. We are doing our best to discourage this form of entry and hope soon to cut it out completely."

This company summarises its views on apprenticeship in a manner which typifies modern thinking and is well worth quoting.

"In any technical staff there are a number of men whom we might designate 'technical hacks' or 'hewers of the technical wood'. It is essential for these to be academically qualified and one might assume that the less gifted of the men with the H.N.C. would fall into this category. Substantially they are those who, during and after their apprenticeship scramble up to the H.N.C. with difficulty.

"The other group of apprentices who obtain the H.N.C. or, via apprenticeship, enter the university, form a hard centre of our technical staff. The more enterprising of these should reach a high 'ceiling' since they have practical training and technical education welded together. The only reason for their failure would normally be defects of personality.

"The product of the 1-3-1 sandwich degree apprentice scheme should produce the most consistently good results —higher orders of intelligence plus appropriate training plus education."

One engine company says that it finds difficulty in recruiting "people who have a reasonably good technical education, a real interest in engineering and adequate practical experience. We consider that a good engineer should have spent a considerable time in the design office and people with these 'all-round' qualifications are hard to find, more so in the younger age groups."

Another deplores "the modern trend which considers that vast numbers are necessary. To those who have controlled drawing offices it is obvious that manpower can never replace brilliance of thought." It goes on to say that the mechanical side of the Industry has not received the attention that it should and to urge that training schemes should give more time to the principal mechanisms.

DIPLOMA OF TECHNOLOGY

Asked about the Dip. Tech., several companies said that it was too early to give an opinion. Generally, it was welcomed. One comment was "A good innovation, because it gives opportunity to those who could not get or take a place at university and to late developers who could not obtain university entrance qualifications. But will colleges of advanced technology be able to secure teachers of the same standard as universities?"

One company felt that the Dip. Tech. "shows promise of becoming as valuable as a degree." Another view was that it was suitable for "men who would be expected to be in the largest stratum of the technical departments, men who might be regarded as in the category of general-purpose engineers."

POST-GRADUATE QUALIFICATIONS

Mixed views were expressed on the need for men with post-graduate qualifications and in general only a small demand was seen for them. One eminent company states "We do not think that our demand for people with post-graduate qualifications will increase. It is our experience that a graduate matures more quickly in employment with us than in spending the same period of time studying for a higher degree."

Another states "we should certainly be interested in recruiting more men with post-graduate qualifications, but the demand far exceeds the supply at the present time. The difficulty here is that we are mainly interested in recruiting engineers, and as most engineers wish to obtain the two years post-graduate industrial training as soon as possible (to qualify for associate membership of the appropriate institution) there is therefore a shortage of applied scientists staying on at university to undertake research, in comparison with the much larger number of pure scientists who do this."

Several companies expressed appreciation of post-graduate training at the College of Aeronautics and Imperial College. Another view on the subject is given by the company which says that "from the point of view of the engineering industry, as opposed to the chemical industry, the employer tends to be chary of acknowledging research in financial terms since the subject of the research may be of no relevance to the proposed appointment and it is at least debatable whether post-graduate experience is not more appropriately obtained within the Industry. There is also in the background the fear of creating a body of perpetual students never anxious to return to industry to relatively mundane activities."—J.R.C.

New Committee 1960/61—Officers

The office holders for the coming year will be as follows:

Chairman W. G. Wilson
Graduate, Fairey Aviation Co. Ltd.

Hon. Secretary H. Frazer Mitchell
Graduate, Handley Page Ltd.

Hon. Visits Secretary N. R. Craddock
Graduate, Handley Page Ltd.

Hon. Treasurer J. F. Wilby
Graduate, de Havilland Aircraft Co. Ltd.

Hon. Editor C. G. Keil
Graduate, "Aircraft Engineering."

The position of Hon. Lectures Secretary has been discontinued and the duties will be taken over by the Chairman.

Autumn Lecture Programme

As a result of the work being carried out on the new lecture hall there will only be two lectures this autumn. The first, in November, will be on the British Space Programme.

THE LIBRARY

Reviews

THE SCIENTIFIC PAPERS OF SIR GEOFFREY TAYLOR. Vol. I, Mechanics of Solids; Vol. II, Meteorology, Oceanography and Turbulent Flow. *G. K. Batchelor (Editor). Cambridge University Press. 600 pp. and 500 pp. Illustrated. 75s. each.*

Before commencing a new line of investigation a research worker must first find out what has already been written on the subject, both by consulting books and, above all, by reading the original research papers. An enquiry starts by searching the literature and more often, by asking others for the names of scientists who are likely to have made contributions in a particular field. In fact, a lead towards the names is often the best way to start. The same is true to a lesser extent of anyone who wants information on a given subject. Much of the key work will be found in this way and the bibliographies included in the research papers will direct further reading. Thus, in the early days of this century, the mathematical physicist often consulted the collected papers of Lord Rayleigh. Equally today a physicist would turn to the collected papers of Sir Geoffrey Taylor, whose clear exposition and breadth of outlook, in a similar but broader realm, have rarely been equalled.

G. I. Taylor's collected papers will fill four volumes, of which the first two have now been published by the Cambridge University Press. Our regret is the absence of any clue as to what is in each volume other than the undertaking by the editor, Dr. G. K. Batchelor, that a complete list of the papers in all four volumes will be provided at the end of Volume IV. Had it been possible, this list could with advantage have appeared in each volume, especially as the editor explains in his preface that the divisions between the different aspects of fluid mechanics in Volumes II, III and IV are not sharp. Within each volume the papers have been arranged in chronological order; Volume I includes all his papers on the mechanics of solids and Volume II contains papers on meteorology, oceanography and turbulent flow

Both volumes have been admirably produced as regards text, mathematics, line diagrams and photographic reproductions. They have been carefully edited. The first contains 41 papers in a volume of nearly 600 pages and the second 45 papers in some 500 pages; each is priced separately at 75s., a reasonable cost. Sir Geoffrey is the eighteenth in a most distinguished line of scientists whose collected papers have been published by this press. The list of Contents in each volume gives the title of the paper, its co-author if any, its date and place of original publication. A high proportion were published by the Royal Society, a few were published abroad and some are now made generally available for the first time.

Volume I commences with papers on the use of soap films for solving torsion and flexure problems and were written while he was stationed at the R.A.E. in the First World War. Many papers follow on the distortion and plastic extension of single crystals of aluminium, iron, beta brass, etc. The general problems of the shear and distortion of metals retained his interest over many years, and after a break during the Second World War he returned again to the subjects of elasticity and plasticity. His interest in the war effort was shown by papers on the propagation of earth waves in an explosion, the mechanical properties of cordite, and the effects of impact loads. His James Forrest lecture was entitled "The testing of materials at high rates of loading." This volume contains his famous work on dislocation theory.

The phenomenon of turbulence and its effects in the atmosphere and in problems of fluid mechanics provides the main theme of the second volume, but it also contains a wide range of geophysical problems. The early papers on meteorology indicate the direction in which his ideas evolved up to his well-known work on the statistical theory of turbulence. The earliest on eddy motion in the atmosphere was published in 1915 and was soon followed by others on turbulence in the lower atmosphere and on the dissipation of eddies. His five papers on Statistical Theory and that on the Spectrum of Turbulence, published by the Royal Society between 1935 and 1938, are all included in this volume. We find also papers on diffusion in the atmosphere, formation of fog, tidal friction and tidal oscillations, and the stability of stratified fluids. In fact, this volume will interest meteorologists, oceanographers, and geophysicists, as well as scientists concerned with fluid mechanics.—J. L. NAYLER.

EXPERIMENTAL STRESS ANALYSIS, Vol. XVII, No. 1. *C. V. Mahlmann and W. M. Murray (Editors). Society for Experimental Stress Analysis, Cambridge 39, Mass. 180 pp. Illustrated. No price quoted.*

How is one to review the Proceedings of the Society for Experimental Stress Analysis? It is a regular thing, comes out twice a year in the States and has no parallel yet in this country—more's the pity.

If you need to consider the merits and demerits of strain gauges for high temperature use; if you want to review the unsolved problems of high temperature instrumentation; if you are interested in the techniques of creep testing or the facility for elevated temperature test at Wright Field: or if you want to sense loads under thirty feet of hot water, you will find help here. And that comprises but five sixteenths of the whole.

Another quarter is devoted to examination by strain gauges and photoelasticity of stresses in the more awkward parts of nuclear power plant and suchlike components; three sixteenths to an atomic blast simulator, to explosive means to achieve high rates of strain and to photoelastic determination of stress distribution in a cone with a band of pressure at the vertex; and another three sixteenths to thermally induced buckling in turbine wheels, to photoelastic measurement of stresses round rivets and to the applications of semiconductor transducers.

The whole is prefaced by the 1957 William S. Murray Lecture on the simulation of shock and vibration environments; and no one who is interested in such matters can afford not to have this volume and the preceding issues.

The early pages are worth more than a glance; the Committees comprise catalogue of equipment, clinics and workshop sessions, creative thinking, exhibits and library, besides local sections and nine other administrative committees with duller titles. The list of corporation members includes about eighty well known establishments and among them three British, two being aircraft firms. Is three eightieths support for a purely United States activity the best we can do?—H. L. COX.

WRITING IN INDUSTRY. Vol. I. *S. Mandel (Editor). Polytechnic Press, New York, 1959. 121 pp. Diagrams.*

Selected papers from the Proceedings of the Conference on Writing and Publication in Industry, Brooklyn Polytechnic, 1959. Among the outstanding contributions published are "Production and Design Problems in Engineering Publications" (A. Eckstein) and "Journalistic Aspects of Science Writing" in which the author (Science Editor of the *New York Times*) makes the candid admission: "To my mind

there is not a single American scientist who can write." This is certainly an exaggeration, or why should American books sell so well in this country? Nevertheless, he is probably correct in attributing so much poor writing to the educational system in America, which lays insufficient stress on the importance of good English and good expression.—G. PARR.

Additions to the Library

Advances in Applied Mechanics. Volume VI. H. L. Dryden and Th.von Kármán (*Editors*). Academic Press, New York. 1960. 294 pp. Diagrams. 9 dollars. *To be reviewed.*

Aerodynamics of Powered Flight, The. R. Carroll. John Wiley, London and New York. 1960. 275 pp. Diagrams. 68s. *To be reviewed.*

Aerospace Year Book 1960, The. Aerospace Industries Association. American Aviation Pubs., Washington. 1960. 478 pp. 10 dollars. Although this is described as the forty-first annual edition it is actually the first under this exact title. Hitherto the work has been *Aircraft Year Book*. However, there is little change in the style and those who are accustomed to this excellent reference book to the Industry in America will have no difficulty in finding their way about. The book is a necessity to those who require to keep abreast of the achievements of the two interplanetary contestants, just as it is to those who want a quick and encyclopaedic reference to the current conventional aircraft programme. An interesting chronology of aeronautics in the United States contrives to go back to 1784 and this feature is expanded, for 1959, into a "day by day" diary. If only the book contained a who's who one could not ask for more.

Aircraft and Missile Design and Maintenance Handbook. C. A. Overbey. Macmillan, New York. 1960. 369 pp. Diagrams. 68s. *To be reviewed.*

Basic Electronics. Six Parts. van Valkenburgh, Nooger and Neville, Inc. The Technical Press, New York. 1959. Approx. 100 pp. per Part. Illustrated. 12s. 6d. per Part. 66s. per complete set. *To be reviewed.*

British Civil Aircraft 1919-59. Volume II. A. J. Jackson Putnam, London. 1960. 595 pp. Illustrated. 63s. *To be reviewed.*

Cours de Mécanique du vol. A. Turcat. Second Edition. Dunod. Paris. 1960. 160 pp. Diagrams. 20 NF. *To be reviewed.*

Design and Performance of Gas Turbine Power Plants. High Speed Aerodynamics and Jet Propulsion. Volume XI. W. R. Hawthorne and W. T. Olson (*Editors*). Oxford University Press, London. 1960. 563 pp. Illustrated. 5 gns. *To be reviewed.*

Diffraction Gratings as Measuring Scales. J. Guild. Oxford University Press, London. 1960. 211 pp. Illustrated. 35s. Written to assist engineers and scientists who are interested in the practical application of the Moiré fringe method to exceptionally fine measurement and to the automatic control of machines working to extremely fine limits.

Forty-Fourth Annual Report of the National Advisory Committee for Aeronautics, 1958. U.S.G.P.O. Washington, (H.M.S.O.) 1959. 1494 pp. Illustrated. 10.50 dollars. With this volume NACA Reports, as such, finish. The first volume, published in 1915 contained Report No. 1 (by Hunsaker) and the present volume, with nearly five times as many larger, papers contains No. 1392. The "letter of submittal" to the President contains what may well be a historic sentence. Dated 30th September, 1958 it says "At the close of business on this date the National Advisory Committee for Aeronautics goes out of existence". The signature is that of the Chairman, James H. Doolittle.

Future of British Air Transport, The. Second Report. Air League of the British Empire, London. 1960. 21 pp. Illustrated. No price. Takes in such contemporary problems as the supersonic transport and S/V.T.O.L.

Guide to Hygiene and Sanitation in Aviation. W.H.O. Expert Committee on Hygiene and Sanitation in Aviation. World Health Organisation, Geneva. 1960. 51 pp. Illustrated. 3s. 6d. A reprint from the W.H.O. Expert Committee on Hygiene and Sanitation in Aviation (1959) First Report. Subjects dealt with are general hygiene; ground installations; aircraft sanitary equipment; ground facilities other than airports (*e.g.* rest houses); specific recommendations on sanitation with regard to water, food, wastes; vector control, *i.e.* insects, mosquitoes, (yellow fever, anopheles), flies and rodents. There are 28 references for further reading. Obtainable from Her Majesty's Stationery Office.

Heliport Design Guide. Federal Aviation Agency. U.S.G.P.O. Washington (H.M.S.O.) 1959. 26 pp. Diagrams. 2s. 8d. A general guide for the development of a heliport from comparatively undeveloped one-operation types to more fully developed ports capable of multiple operations.

Hypersonic Flow. Edited by A. R. Collar and J. Tinkler. Butterworths Scientific Publications. London. 1960. 432 pp. Illustrated. 70s. *To be reviewed.*

Interavia ABC, 1960. Interavia, Geneva 1960. 1280 pp. £4. The mixture as before, but at an increase in price of 14 shillings. It is, of course, unique in its coverage but there is always the faint fear, when using it, that the information on individuals may not be quite up to the moment.

International Scientific Congress on Jet Stream and Mountain Waves. Centro di Volo a Vela del Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin. 1959. 144 pp. Illustrated. 2,200 Lira. The Proceedings of the Congress, held in Turin in June 1959. Three of the 25 papers are by authors from the United Kingdom; E. Chambers of B.O.A.C. and K. Wood of B.E.A., on operational experience of jet streams and clear air turbulence and R. S. Scorer on turbulence produced in waves of large amplitude. Other papers are in English from the Spanish Meteorological Service, the Universities of Innsbruck and of Oslo and the German Research Institute for Soaring Flight.

Leichtbau. Heinrich Hertel. Springer-Verlag, Berlin. 1960. 526 pp. Illustrated. DM. 67.50. *To be reviewed.*

Magneto-Fluid Dynamics. AGARD, NATO, Paris, 1960. 30 pp. No price. This is AGARD's first Bibliography, prepared by A. G. Vannucci. It is in two parts: first, 692 references in abc order of author, with list of abbreviations, an addendum of 67 items, a bibliography by subjects and an index to authors (necessary because of multiple authorship) and, secondly, each item of the bibliography set out in a way suitable for mounting on 5×3 cards but with only the title, author and an abstract given. It is thus necessary to add any classification notes.

Mathematics Education and Industry. A Record of a Conference of Teachers, Research Scientists, and Industrialists held at the University of Liverpool. The Times Publishing Co., London. 1959. 156 pp. Diagrams. 7s. 6d.

Missile Aerodynamics. J. N. Nielsen. McGraw-Hill, New York. 1960. 450 pp. Diagrams. 97s. *To be reviewed.*

Other Side of the Moon, The. U.S.S.R. Academy of Sciences. Translated by J. B. Sykes. Pergamon Press, Oxford. 1960. 36 pp. Illustrated. 10s. 6d. A colourfully bound, if somewhat slender book describing the Soviet achievement of photographing the reverse side of the Moon by Lunik III. As a translation of the Russian text recently released and also as a record of the lectures given by Prof. Alla Masevitch, Vice-President of the U.S.S.R. Astronomical Council, in this country last February, the book is an excellent record. However, it is devoid of all but the barest technical details of the launching, materials and construction, or instrumentation of the satellite, and its associated ground equipment.

Principles of Guided Missiles and Nuclear Weapons. U.S. Bureau of Naval Personnel. U.S.G.P.O., Washington (H.M.S.O.). 1959. 283 pp. Illustrated. 18s. The second of

a three-volume series dealing with Naval weapons. Eleven chapters deal with guided missiles and three with nuclear weapons. An idea of its level can be obtained from Appendix A which is entitled "Introduction to basic electricity and electronics". The next volume will deal with specific missiles and nuclear weapons.

Progress in Solid Mechanics. I. N. Sneddon and R. Hill (*Editors*). North-Holland Publishing Co., Amsterdam. 1960. 448 pp. Diagrams. £5. *To be reviewed.*

Propulsion Systems for Space Flight. W. R. Corliss. McGraw-Hill, London. 1960. 300 pp. Diagrams. 77s. 6d. *To be reviewed.*

Rakieta Miedzyplanetarna. E. Bialoborski. Panstwowe Zaklady Wydawnictw Szkolnych, Warsaw. 1960. 379 pp. Illustrated. No price given. Judging by the illustrations and the bibliography this is a book about Interplanetary flight and satellites. It was presented by the author and one suspects that were it translated it would be one of the few books on the subject that is able to discuss the achievements of both sides of the Iron Curtain. The bibliography (which is conveniently broken down to quote such figures) contains 10 Polish items, 5 Russian, 6 German, 8 English and 3 French. The Librarian is willing to make this book available to anybody who would care (and is able) to translate it.

Rarefied Gas Dynamics. F. M. Devienne. (*Editor*). Pergamon Press, Oxford. 1960. 442 pp. Diagrams. Illustrated. Bibliography. £6. This is the third volume in the Pergamon International Series on Aeronautical Sciences and Space Flight in Division IX (Symposia), not to be confused with Division VII (Astronautics) the first two volumes of which are also Symposia. The present volume contains the papers read at the First International Symposium, held at Nice, on rarefied gas dynamics and aerothermodynamics, and under the auspices of the Paris Faculty of Sciences. There are 29 papers by authors from several countries, including Japan, Sweden and Poland, the majority being American; a few are in French. The only British paper describes the A.R.D.E. low-density wind tunnel.

Scientific Papers of Sir Geoffrey I. Taylor, The. In Two Volumes. G. K. Batchelor (*Editor*). Cambridge University Press, London. 1960. 593 pp. and 515 pp. Illustrated. 75s. per volume. *Reviewed in this issue.*

Strike from the Sky. The Story of the Battle of Britain. A. McKee. Souvenir, London. 1960. 288 pp. Illustrated. 21s. *To be reviewed.*

Structural Damping. J. E. Ruzicka (*Editor*). Pergamon, London. 1960. 165 pp. Illustrated. 30s. Six papers and a bibliography from a colloquium held at the American Society of Mechanical Engineers' annual meeting in December 1959. It was sponsored by the Shock and Vibration Committee of the Applied Mechanics Division. The book is rounded off by a 100-item bibliography in alphabetical order of author.

Symposium: Army-Navy Instrumentation Progress. U.S. Army Signal Corps. Bell Helicopter Corp., Fort Worth. 1959. 451 pp. Illustrated. No price. Sponsored by the Signal Corps and with the co-operation of Bell Helicopters, Douglas, Electric Boat Co., and Sperry Rand, this contains the unclassified papers of the meeting, held at Dallas.

Theory of Wing Sections, Including a Summary of Airfoil Data. I. H. Abbott and A. E. von Doenhoff. Dover Publications, New York (Constable, London.), 1959. 693 pp. Figures. 24s. For many years, the Librarian of the Society has been hard put to it to keep up with the requests for this book, originally printed in 1949 and soon out of print. It is hoped that the pressure will now be relaxed thanks to the enterprise of Dover Publications who have reprinted the original edition with no additions but with mistakes in the original corrected. The book was first reviewed in the JOURNAL on page 392 in 1950 when the reviewer said "Messrs. Abbott and Doenhoff have now collected the bulk of the American work (on wing sections) and presented it in this book in a form which will be invaluable to the aeronautical engineer. Not only are the main experimental data exhaustively tabulated and presented in graphs, but the essentials of the theory are simply and clearly outlined and a comprehensive list of references is provided for further detailed reading."

There Shall be Wings: a History of the Royal Canadian Air Force. L. Roberts. Harrap, London. 1960. 290 pp. Illustrated. 21s. *To be reviewed.*

Turbulent Flows and Heat Transfer. C. C. Lin (*Editor*). Oxford University Press, London. 1959. 549 pp. Illustrated. 105s. *To be reviewed.*

Units, Dimensions and Dimensionless Numbers. D. C. Ipsen. McGraw-Hill, London. 1960. 236 pp. 50s. 6d. *To be reviewed.*

Wave Propagation in a Random Medium. Lev A. Chernov, translated by R. A. Silverman. McGraw-Hill. 1960. 168 pp. 58s. A bound volume containing the photo-reproduction of the typescript of a monograph on the theory of the subject. Part I studies the problem of wave propagation using the ray approximation. Part II deals with the diffraction theory of wave propagation. Part III examines the question of how fluctuations in the incident wave affect the diffraction image formed by a focusing system. Some theoretical deductions are compared with experimental data.

Writing in Industry. Volume I. S. Mandel (*Editor*). Polytechnic Press, Brooklyn. 1959. 121 pp. Diagrams. No price. *Reviewed in this issue.*

Reports

AERODYNAMICS

BOUNDARY LAYER *see also* COMPRESSIBLE FLOW
THERMO-AERODYNAMICS
TESTING AND INSTRUMENTS

On surface pressure fluctuations in turbulent boundary layers. G. M. Lilley and T. H. Hodgson. C.o.A. Note 101. *April* 1960.
Existing work on the pressure fluctuations in turbulent shear flows is briefly reviewed with special reference to the problem of wall turbulence. An approximate theory for the pressure fluctuations on the wall under both a turbulent boundary layer and a wall jet is given. Appendices deal with the necessary extensions to the analysis to fit the velocity correlation functions as measured by Grant (1958), the effects of time delay and eddy convection.—(1.1.3.1×1.6.1).

Preliminary experimental investigation of effect of free-stream turbulence on turbulent boundary-layer growth. S. J. Kline et al. *N.A.S.A. T.N. D-368. March* 1960.
The results of a preliminary experimental investigation of the effect of free-stream turbulence on the characteristics of the turbulent boundary layer on a flat plate are presented.—(1.1.3.1 ×1.4.2×1.5.1).

COMPRESSIBLE FLOW *see also* POWER PLANTS

Some instabilities arising from the interactions between shock waves and boundary layers. N. C. Lambourne. C.P. 473. 1960.
Information concerning the flow fluctuations and instabilities arising from shock-induced separation in the flow over aerofoils and wings is reviewed. The influence this phenomenon has on the oscillatory behaviour of aerofoils and control surfaces is briefly discussed. A more detailed consideration is devoted to a recent investigation at the N.P.L. into the part played by shock-induced separation in the instability of a control surface.—(1.2.3.2×1.1.4.4×1.10.0.1×1.3).

Supersonic axisymmetric conical flow bordering on a symmetrical parallel flow through a shock wave. G. L. Grodzovsii. R.A.E. Lib. Trans. 884. *March* 1960.
It is shown that four types of flows are possible involving

supersonic axisymmetric conical flow adjacent to symmetrical parallel flow through a conical shock wave. Examples are calculated for the two types—convergent conical flow behind a conical shock wave and divergent conical flow upstream of a conical shock wave.—(1.2.3.2).

On base pressures at high Reynolds numbers and hypersonic Mach numbers. J. D. Whitfield and J. L. Potter. A.E.D.C.-T.N.-60-61. March 1960.
A tentative method for estimating base pressures at hypersonic Mach numbers and at large Reynolds numbers is described. Both blunt and sharp nosed shapes are treated. The procedure is based on existing empirical methods but modifications are made to deal with short, blunt bodies. Refinement and definition of the limitations on the method must await experimental data covering a greater range of variables.—(1.2.3.1).

On rotational flow past thick airfoils. A. Kogan. Israel Inst. Tech. Dept. Aero. Eng. Report 1. *Feb.* 1959.
The inviscid rotational supersonic flow behind the shock wave attached to the sharp leading edge of an aerofoil is studied by a transformation of co-ordinates which introduces the Crocco stream function ψ as independent variable. Using expansions in power series of ψ an iterative process is developed for the determination of pressure distribution along the aerofoil surface. For the special case of near-shock-detachment flow a simple approximation is derived for flow in the whole region between the aerofoil and the shock wave.—(1.2.3.2×1.10.1.1).

CONTROLS *see* COMPRESSIBLE FLOW
STABILITY AND CONTROL
WINGS AND AEROFOILS
TESTING AND INSTRUMENTS
AEROELASTICITY

FLUID DYNAMICS *see* BOUNDARY LAYER

INTERNAL FLOW *see* BOUNDARY LAYER
TESTING AND INSTRUMENTS
POWER PLANTS

LOADS *see* BOUNDARY LAYER
WINGS AND AEROFOILS

PERFORMANCE *see also* STABILITY AND CONTROL

Some requirements for the efficient attainment of range by airborne vehicles. M. Arens. Israel Inst. Tech. Dept. Aero. Eng. Report 3. *Sept.* 1959.
The efficiency of attaining range using either a level-cruise or ballistic trajectory can be evaluated by use of a suitable range factor for both trajectories. Use of this factor also allows comparison between aircraft using power plants of different specific weight and fuel consumption. The ballistic trajectory is examined, and the region in which it is inherently superior to a level-cruise trajectory is described as a function of cruising L/D and range. The optimum speeds for cruising flight are determined, and a criterion for the evaluation of the relative merits of accelerating power plants is established.—(1.7).

Optimum staging of cruising aircraft. M. Arens. Israel Inst. Tech. Dept. Aero. Eng. Report 5. *Nov.* 1959.
The condition for optimal staging of cruising aircraft is derived as a function of aircraft and power plant performance, aircraft mass ratio, and payload ratio. Explicit solutions for the optimum relationship between the stage parameters for different type aircraft are presented, and the limitation on the usefulness of staging is investigated. Finally, a number of optimally staged aircraft are compared with single stage aircraft covering a range of 6,000 miles.—(1.7).

STABILITY AND CONTROL *see also* EXTRA-ATMOSPHERIC TECHNOLOGY

Wing-on and wing-off longitudinal characteristics of an airplane configuration having a thin unswept wing of aspect ratio 3, *as obtained from rocket-propelled models at Mach numbers from* 0·8 *to* 1·4. *C. L. Gillis and A. J. Vitale. N.A.S.A. T.N. D-*7. *March* 1960.
Flight tests were conducted on three rocket-propelled models of an aeroplane configuration, two models having thin unswept wings of aspect ratio 3 and hexagonal aerofoil sections, and the third having no wing. The two winged models had wings of different stiffness characteristics. Aerodynamic derivatives defining the static and dynamic longitudinal stability, control, trim, and drag characteristics of the configuration were obtained over a Mach number range from 0·8 to 1·4. For some of the aerodynamic derivatives the separate effects of the wing, tail, and fuselage were determined.—(1.8.2.2×1.12.2×1.10.2.2).

Force-test investigation of the stability and control characteristics of a ¼*-scale model of a tilt-wing vertical-take-off-and-landing airplane. L. P. Tosti. N.A.S.A. T.N. D-*44. *March* 1960.
The model had two 6-blade dual-rotating propellers that were not interconnected mounted on a wing that could be tilted up to an incidence angle of about 90° for vertical take-off and landing.—(1.8.1.2×1.8.2.2×3.12×29).

Flight investigation of stability and control characteristics of a ¼*-scale model of a tilt-wing vertical-take-off-and-landing airplane. L. P. Tosti. N.A.S.A. T.N. D-*45. *March* 1960.
Tests were made of hovering flights in still air, vertical take-offs and landings, and slow constant-altitude transitions from hovering to forward flight. The model had two 6-blade dual-rotating propellers mounted on a wing tiltable up to an incidence angle of approximately 90°. Two wing spans were used. The model had conventional aileron, rudder, and elevator controls for forward flight. For hovering flight the ailerons provided yaw control, an air jet at the tail provided pitch control, and differential total pitch of the propellers provided roll control.—(1.8.0.2×3.12×29).

*Wind-tunnel investigation of longitudinal aerodynamic characteristics of three propeller-driven V.T.O.L. configurations in the transition speed range, including effects of ground proximity. R. E. Kuhn and W. C. Hayes. N.A.S.A. T.N. D-*55. *Feb.* 1960.
The investigation used a semispan wing model with two propellers arranged so that their slipstreams covered most of the wing semispan. A sliding flap and a Fowler flap were fitted so that the model could be tested as a tilt-wing configuration, a deflected-slipstream configuration, or a combination tilt-wing-deflected-slipstream configuration. Some measurements of the flow field (angularity and dynamic pressure) in the general location of a horizontal tail were made.—(1.8.2.2×1.7×1.3.4×1.12.1.1×3.12×29.9).

Flight investigation of pilot's ability to control an airplane having positive and negative static longitudinal stability coupled with various effective lift-curve slopes. R. F. Brissenden et al. *N.A.S.A. T.N. D-*211. *Feb.* 1960.
The study included the determination of the ranges of possible human-pilot control of the variable stability aeroplane at various stability levels coupled with various reduced effective lift-curve slopes.—(1.8.2.2×13.2).

Longitudinal aerodynamic characteristics of a high-subsonic-speed transport airplane model with a cambered 40° *sweptback wing of aspect ratio* 8 *at Mach numbers to* 0·96. *A. R. Heath. N.A.S.A. T.N. D-*218. *Feb.* 1960.
The longitudinal characteristics of a complete high-subsonic-speed transport configuration with a cambered wing have been measured. The wing was cambered for a lift coefficient of 0·514, had a taper ratio of 0·3, and had N.A.C.A. 65A-series aerofoil sections. Modifications to the model such as changes in the fuselage shape, leading edge extensions on the wing, special wing bodies, and lower surface ridges on the wing were investigated to determine the effects on the longitudinal stability and maximum lift-drag ratio. The investigation covered a Mach number range from 0·40 to 0·96.—(1.8.2.2×1.10.2.2).

*Subsonic wind-tunnel investigation of the aerodynamic effects of pivoting a low-aspect-ratio wing to large yaw angles with respect to the fuselage to increase lift-drag ratio. T. G. Gainer. N.A.S.A. T.N. D-*225. *March* 1960.
Three wing plan forms were tested—a delta, a diamond, and a rectangle—with the wing pivoted at angles between the wing and fuselage centre lines from 0° to 109°. The investigation was made in the Langley high speed 7 × 10 ft. tunnel at a Mach number of about 0·4 and a Reynolds number of about 3×10^6. Lift, drag, pitching moment, and rolling moment data were obtained through an angle of attack range from −4° to about 24°.—(1.8.1.2×1.8.2.2×1.10.2.2).

Experimental determination of the effects of frequency and amplitude of oscillation on the roll-stability derivatives for a 60° *delta-wing airplane model. L. R. Fisher. N.A.S.A. T.N. D-*232. *March* 1960.—(1.8.1.2×1.10.2.2).

THERMO-AERODYNAMICS

Stagnation-point heat-transfer rate measurements in the unexpanded flow of the N.P.L. hypersonic shock tunnel. B. D. Henshall. C.P. 468. 1960.
Thin-film resistance thermometers have been used to determine the heat transfer rate to the stagnation point of ¾ in. diameter glass spheres in shock tube flows in air with real gas stagnation temperatures up to 6,000°K.—(1.9.1×1.12.1.3).

A simplified theory of skin friction and heat transfer for a compressible laminar boundary layer. G. M. Lilley. C.o.A. Note 93. *Jan.* 1959.
The compressible laminar boundary layer equations for a perfect gas in steady flow at arbitrary external Mach number and wall temperature distribution are solved approximately by the combined use of the Stewartson-Illingworth transformation and application of Lighthill's method to yield the skin friction and rate of heat transfer. Appendices give the necessary modifications to the method for the separate cases of very low Prandtl number and for the flow near a separation point. One appendix describes Spalding's method for improving the accuracy of wall value of shear stress and rate of heat transfer distributions along a wall having a non-uniform temperature distribution.—(1.9.1×1.1.1.4).

WINGS AND AEROFOILS *see also* COMPRESSIBLE FLOW
STABILITY AND CONTROL
TESTING AND INSTRUMENTS

The rotating flap as a high-lift device. L. F. Crabtree. C.P. 480. 1960.
A wing in an airstream can develop extremely high values of lift coefficient if it is rotated about a spanwise axis. A more practical development of this system is a fixed mainplane with a rotating trailing-edge flap. The results of some little-known German research on both systems have been collected together and are presented in compact form together with some further analysis.—(1.10.1.2×1.3.4).

Pressure distribution on symmetrical wing sections at near sonic speeds. J. Rotta. R.A.E. Lib. Trans. 876. *Feb.* 1960.
A method is developed for the approximate determination of the pressure distribution on symmetrical wing sections in two-dimensional near sonic flow, based partly on experimental observations. The method has been applied to the symmetrical circular arc section and the results are compared with those from other methods and by experiments.—(1.10.1.1×1.6.1).

Aerodynamic properties of swept-back and delta wings near the ground. F. Thomas. R.A.E. Lib. Trans. 882. *March* 1960.
A method based on the extended lifting-line theory is given which permits the calculation of the lift distribution near the ground for aerofoils of arbitrary plan form, particularly swept-back delta wings. The ground effect is taken into account by the reflection method. The velocities induced by the reflected aerofoil at the actual aerofoil considered are calculated in accordance with a method given by K. Gersten.—(1.10.0.2).

Effects of a lower surface jet on the lift-drag ratio of a 45° *sweptback wing at a Mach number of* 2·01. *E. J. Landrum. N.A.S.A. T.N. D-*183. *March* 1960.
The effects of jet interference were determined for an angle-of-attack range from −2° to 7° for various jet deflections inclined toward the trailing edge. The Reynolds numbers were $1{\cdot}5\times10^6$ and $2{\cdot}8\times10^6$ based on the mean aerodynamic chord.—(1.10.2.2).

The transonic characteristics of a family of two-dimensional symmetrical double wedge profiles. Part I, details of the programme and the zero-lift results. R. J. Sandeman. A.R.L. Report A 114. *Aug.* 1959.
A systematic programme of research into the transonic characteristics of four profiles has been conducted in the A.R.L. transonic wind tunnel. The following results have been obtained for natural and fixed boundary layer transition; (*i*) static pressure distributions, (*ii*) C_L, C_M and C_D from strain gauge force measurements, and (*iii*) shadowgraph observations of the flow behaviour.—(1.10.2.1×1.12.1.2).

High speed wind tunnel tests on a straight wing having aerodynamic sweep. H. G. Darling and R. J. Sandeman. A.R.L. Report A. 116. *Aug.* 1959.
A method has been developed of obtaining aerodynamic sweep on a straight wing by the suitable choice of spanwise variation in section profile. To determine the high speed characteristics of the wing, pressure distributions and strain gauge force measurements were obtained at Mach numbers up to 0·95 on a "two-dimensional" model.—(1.10.2.1).

TESTING AND INSTRUMENTS *see also* STABILITY AND CONTROL
THERMO-AERODYNAMICS
WINGS AND AEROFOILS

Calculation of the recoil of a shock tube. B. A. Woods. C.P. 486. 1960.
The method for calculating the unsteady pressure force acting on the high pressure end of a shock tube after the rupture of the diaphragm is set out. For air or hydrogen a simple closed expression for the pressure is obtained, and the first and second integrals with respect to time are given.—(1.12.1.3).

The centre-line Mach-number distributions and auxiliary-suction requirements for the A.R.A. 9 ft. × 8 *ft. transonic wind tunnel. A. B. Haines and J. C. M. Jones. R. & M.* 3140. 1960.—(1.12.1.2).

A note on the theory of the Stanton tube. G. E. Gadd. R. & M. 3147. 1960.
Existing theories for the Stanton tube are critically reviewed, and a simple method outlined which predicts the calibration function of high Reynolds numbers to the right order of magnitude.—(1.12.5×1.1.3.1).

Effect of a variable-geometry diffuser on the operating characteristics of a helium tunnel designed for a Mach number in excess of 20. *P. J. Johnston and R. D. Witcofski. N.A.S.A. T.N. D-*237. *Feb.* 1960.
An experimental investigation has been conducted in a 3 in. helium tunnel equipped with a conical nozzle and operating at a Mach number of 20 to determine the effectiveness of variable-geometry supersonic diffusers in decreasing the pressure ratio required to maintain flow. Four diffuser entrance wall lengths were investigated.—(1.12.1.3×1.5.1.4).

Problémes de la surface portante annulaire traités par le méthode des analogies rhéoélectriques. G. Hacques. Pubs. Sc. et Tech. 358. 1960. (*In French*).
The problem of the theoretical performance of an annular wing is approached from the method of rheoelectric analogy within the limits of linearised lifting surface theory. Aerodynamic effects due to the variation of the wing geometry and its profile are analysed: annular lifting system, wing in axial flow, cylindrical wing in three-dimensional flow. The presence of a rotating propeller or a centre body in the interior of the wing is also examined. The principal of an analogue representation of unlimited area of the current function for axially symmetric flow is stated.—(1.12.6×1.10.0.2×18.1).

AEROELASTICITY

Wind tunnel tests on the flutter of a swept and unswept wing with ailerons. H. Hall and J. A. Rein. C.P. 478. 1960.
Details are given of low speed flutter tests on an unswept and 40° swept-back wing, each wing having a half span, quarter chord aileron. The aileron mass balance and hinge stiffness were varied in the tests. Flutter calculations were made for both wings.—(2×1.3.1.1).

AIRCRAFT

See also AERODYNAMICS—STABILITY AND CONTROL

Étude en courant plan d'une plateforme à effet de sol. P. Poisson-Quinton. O.N.E.R.A. N.T. 57. 1960. (*In French*).
An account of the experimental work at O.N.E.R.A. is given. The wind tunnel experiments, augmented by flow visualisation studies in a water tunnel, are limited to the study of a ground effect platform in two-dimensional flow.—(3.13).

AIRCRAFT OPERATION

See METEOROLOGY

EXTRA-ATMOSPHERIC TECHNOLOGY

See also MISSILES
POWER PLANTS

Effects of nose corner radii, afterbody section deflections, and

a drogue chute on subsonic motions of manned-satellite models in reentry configuration. W. S. Blanchard and S. Hoffman. N.A.S.A. T.N. D-223. March 1960.—(8.2×1.8.1.2×1.8.2.2).

FLIGHT TESTING

See AERODYNAMICS—STABILITY AND CONTROL

INSTRUMENTS AND EQUIPMENT

See AERODYNAMICS—TESTING AND INSTRUMENTS

MATERIALS

See also POWER PLANTS

Initial investigation of arc melting and extrusion of tungsten. F. A. Foyle et al. *N.A.S.A. T.N. D-269. March* 1960.
Tungsten was vacuum arc-cast using direct-current reverse polarity to produce sound ingots. Arc-cast billets and sintered billets were extruded by both conventional low and high velocity processes. Extrusion ratios as high as 45:1 were accomplished. Tensile properties of extruded tungsten, both arc-cast and sintered, are reported.—(21.2.2).

Effect of hardness and other mechanical properties on rolling-contact fatigue life of four high-temperature bearing steels. T. L. Carter et al. *N.A.S.A. T.N. D-270. March* 1960.
The rolling-contact fatigue life of groups of steel balls tempered to various hardness levels was determined at room temperature in the fatigue spin rig and the five-ball fatigue tester.—(21.2.1×31.2.2.2.1.3).

L'essai de microdureté et ses applications. H. Bückle. Pubs. Sc. et Tech. N.T. 90. 1960. (*In French*).—(21.6.1).

MATHEMATICS

The stability of periodic motions in a special case. V. M. Starzhinskii. R.A.E. Lib. Trans.* 883. *March* 1960.
An addendum to two previous papers by the same author and not completely self-contained. The earlier papers extended the Lyapunov method of characteristic constants to cover the general system of two linear differential equations of the first order having periodic piece-wise continuous coefficients, and stability criteria were established. This addendum shows that the stability criteria for non-disturbed motion, which had been proved valid for $\alpha+\beta<0$, are also valid for $\alpha+\beta=0$ with reference to the stability of the trivial solution of the equations considered.—(22.1).

On the choice of suitable functions for solving non linear equations by iterative procedures. J. Guest. A.R.L. Note S.M. 262. *Nov.* 1959.
A simple criterion is established for choosing suitable functions in iterative procedures. This should serve to minimise time spent on unsuitable functions which may not converge to the desired solution.—(22.1).

An investigation of sampling measurement of time varying random signals through information theory. Y. Ishii. Aero. Res. Inst. Tokyo Report 350. *Feb.* 1960.
A quantitative method of analysis of sampling measurement or conversion of time varying random signals is presented. The analysis is developed by deriving a formula which gives the average information amount per unit time obtained through the sampling measurement of a Gaussian random signal. Comparison between sampling and continuous measurement of the signals is also made.—(22.1).

METEOROLOGY

Note on conditions for which data on the power spectra of atmospheric turbulence are required. J. K. Zbrozek and F. Pasquill. C.P. 474. 1960.—(24×5).

MISSILES

A technique for firing dynamically scaled missile models in wind tunnels and for measuring rocket-motor sound and pressure fluctuations. W. J. Alford and K. W. Goodson. N.A.S.A. T.N. D-224. March 1960.
The dynamic-similarity laws are reviewed and found to be applicable to both constant Mach number scaling and constant Froude number scaling. Rocket motors were designed that provided reasonable scaled thrust time histories. The photographic instrumentation was adequate for obtaining flight-path records of the missiles under conditions of high longitudinal velocity. Rocket-motor noise measurements were made at three microphone locations (streamwise) on the lower surface of the wing as the missile traversed the wing.—(25).

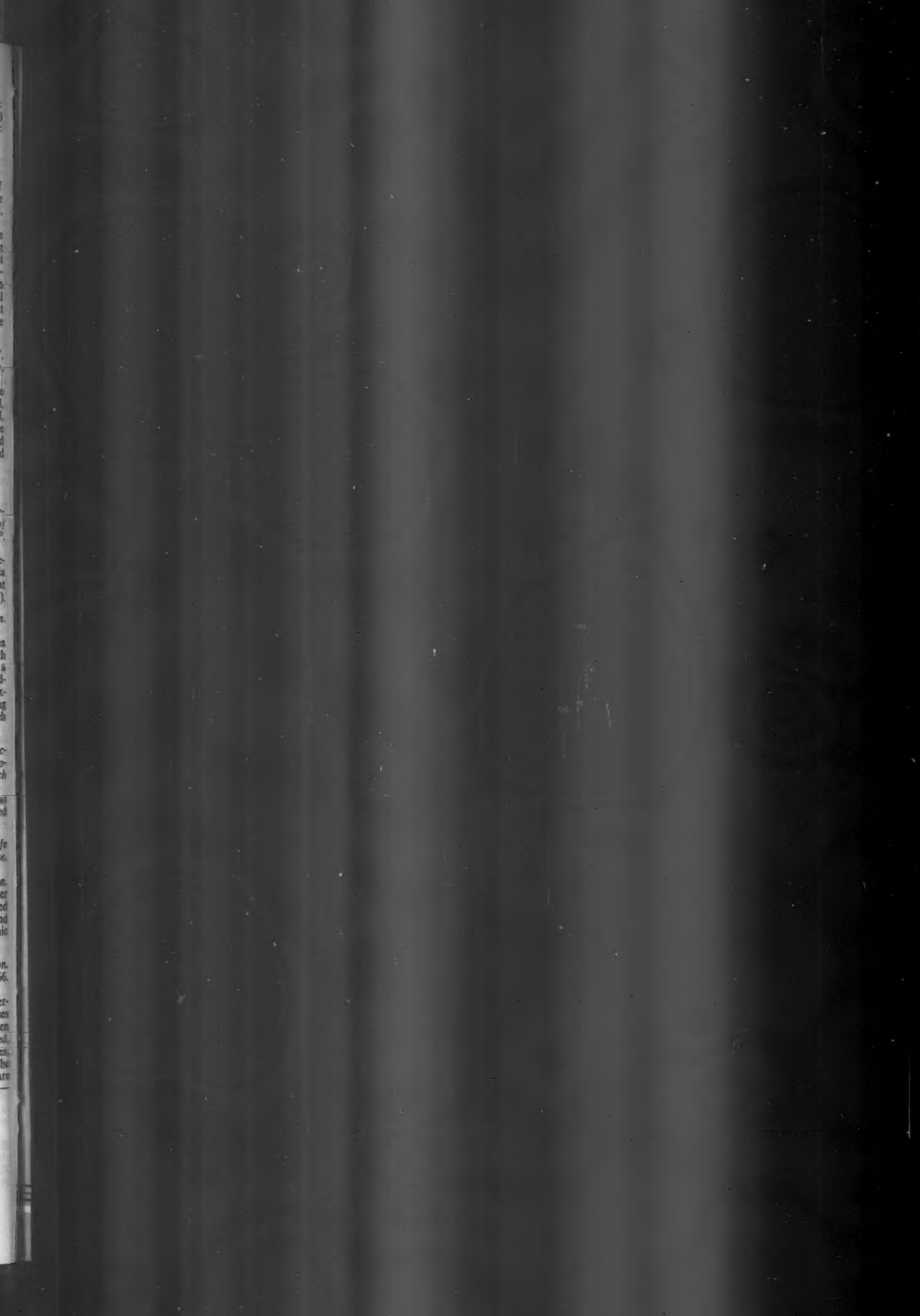
Optimum trajectories with atmospheric resistance. E. W. Graham and B. J. Beane. Douglas Report S.M.-23745. Nov. 1959.
Problems involving the transfer of a rocket vehicle from one point to another with minimum fuel expenditure are considered. The transfer time and the terminal velocity vectors are specified. The first problem studied is one in which atmospheric resistance is the only external force acting on the vehicle. In the second problem both atmospheric resistance and centrally directed gravitational forces are included.—(25.2×8.2).

POWER PLANTS

Turbojet thrust augmentation: flight measurements of the turbine blade cooling accompanying the pre-turbine injection of reheat fuel with an Orenda 14 *engine in a Sabre* 6 *aircraft. E. P. Cockshutt* et al. *N.R.C. Rep. LR-271. Jan.* 1960.
Turbine blade temperature data, obtained with a thermocouple-slipring instrumentation system, are presented for an Orenda 14 engine, which was flight tested both with and without reheat at altitudes ranging from 20,000 to 50,000 feet.—(27.1.2×27.5).

Experimental study of zero-flow ejectors using gaseous nitrogen. W. L. Jones et al. *N.A.S.A. T.N. D-203. March* 1960.
Both bell-shaped and 15°-conical primary nozzles with area ratios of 25:1 were used, and a second conical nozzle with 50:1 area ratio. Both ejector types were investigated over a range of area ratios and length-to-diameter ratios. Second-throat ejectors were studied at several contraction angles. Experimental maximum ejector contraction area ratios and starting performance are given for a range of ejector inlet Mach numbers from 1 to 10.—(27.3×1.5.1×1.2.3).

Experimental determination of the temperature and dynamic-strain environment of a tubular combustor liner in a turbojet engine. P. T. Chiarito et al. *N.A.S.A. T.N. D-204. March* 1960.
Data are presented on some of the environmental factors that must be understood to identify the failure mechanism involved in the frequent cracking of liners.—(27.1×31.2.5.1.2.1).

Effects of melting practice and aluminum coating on the life of GMR 235 *buckets operated at* 1650°*F in a turbojet engine. C. A. Gyorgak* et al. *N.A.S.A. T.N. D-263. March* 1960.
Eight groups of buckets were evaluated in a J33-9 engine. Some buckets were aluminised. The engine test, operated under cyclic conditions was terminated after 269 hours of accumulated rated-speed operating time. Buckets were subjected before and after each test to macrographic inspection, metallographic studies, and hardness determinations.—(27.1×21.2.2×21.4).

Analysis of one-dimensional ion rocket with grid neutralization. H. Mirels and B. M. Rosenbaum. N.A.S.A. T.N. D-266. March 1960.
The rocket consists of a grid that emits ions, a grid that accelerates the ions, and a grid that decelerates the ions and neutralises them (by the emission of electrons). The ion beam between the ion-emitting grid and the neutralisation grid is determined, as is the mixed ion-electron beam downstream (and sometimes upstream) of the neutralisation grid. The forces on the individual grids and the overall thrust of the ion rocket are also determined using momentum-integral concepts.—(27.3×8.2).